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NDE of Reactor Materials

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Outline

- What's NDE?
- NDE for stainless steel and nickel-alloy components
  - Piping
  - Dissimilar metal welds
  - Cast stainless steel
  - Reactor pressure vessel head penetrations
- NDE for reactor pressure vessels
  - Vessel overview
  - Nozzles
  - Underclad cracking
  - Qualification
  - Example of plant-specific vessel NDE issue
- Summary

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What's "NDE"?

- Nondestructive Evaluation
- Inspecting components to see whether they're degraded, without damaging them
  - Cracking
  - Corrosion
  - Fabrication defects
- Methods
  - Ultrasound
  - X-ray
  - Eddy current
  - Dye penetrant

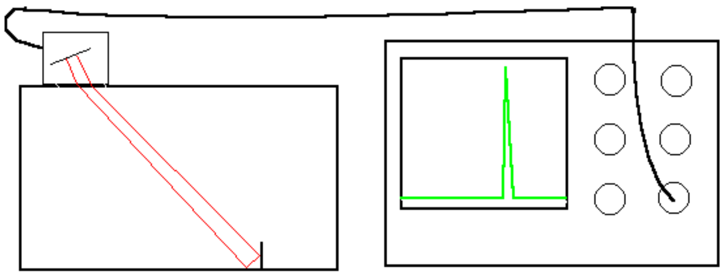
Examine the entire volume (Ultrasound, X-ray)

Examine the surface (Eddy current, Dye penetrant)

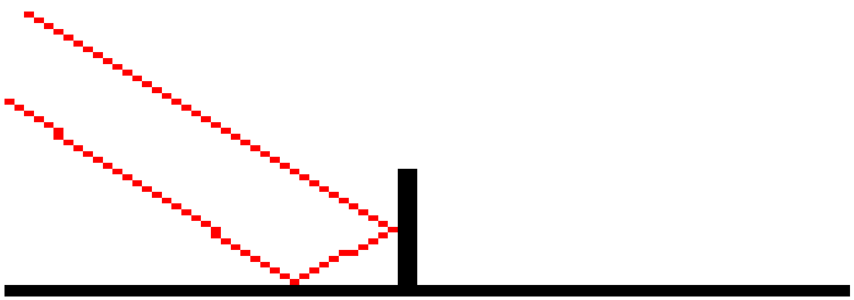
Ultrasonic examination (UT)

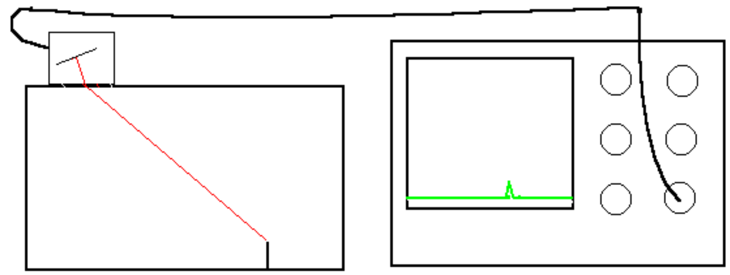
- Principle
  - Interaction of high frequency sound waves with the material (similar to sonar and medical ultrasound)
  - Reveals internal as well as surface breaking features
  - Most widely used inservice inspection method
    - Adaptable to many configurations & materials
    - Provides quantitative flaw location & sizing

Basic pulse-echo UT

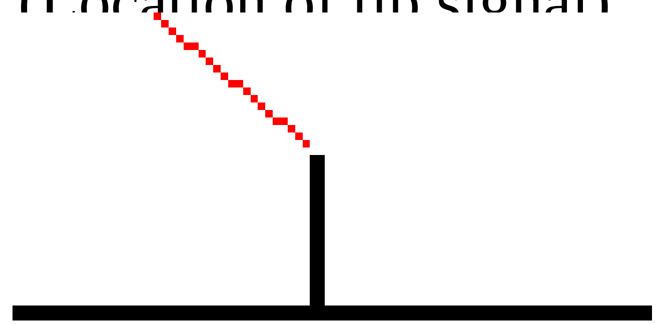


Detection
(“corner echo”)





Sizing
(Location of tip signal)

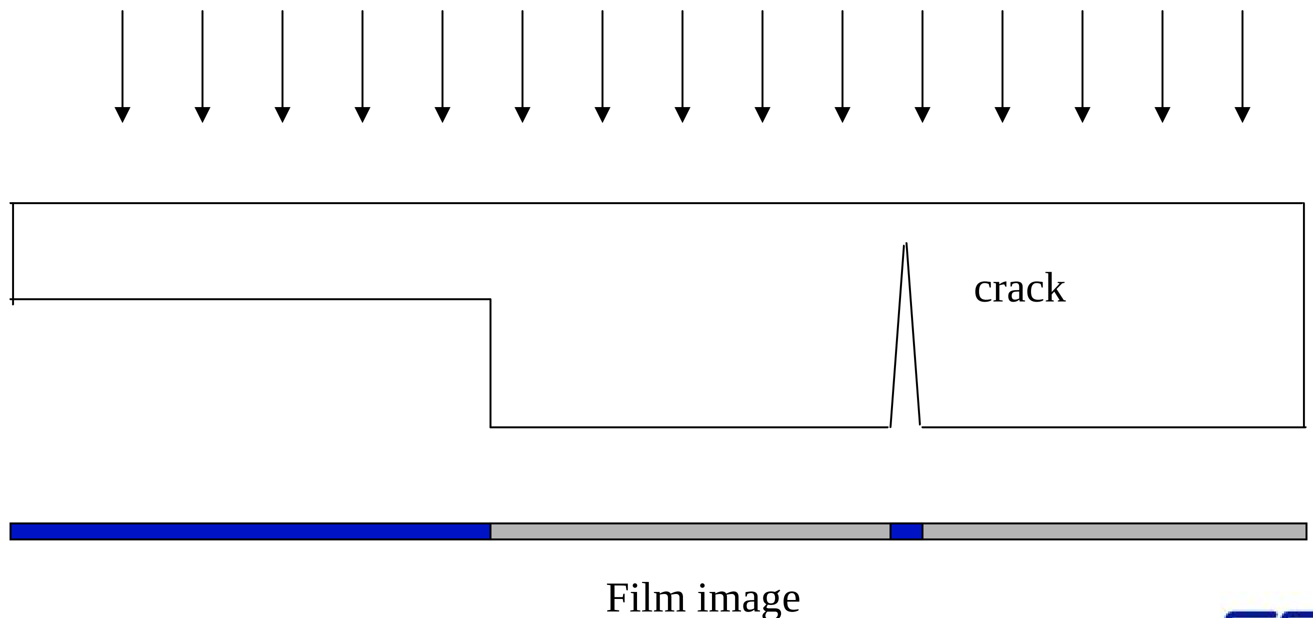


Phased Array UT

- Imaging technique similar to medical ultrasound
- Increasing in importance lately in nuclear NDE
  - Equipment is getting smaller, cheaper, and more powerful
  - Demands for speed are increasing
    - Cost
    - Low dose

Radiographic examination (RT)

- Principle
  - Density changes on film or solid state detector caused by absorption differences in a component reveal internal features
  - Volumetric method



Radiography

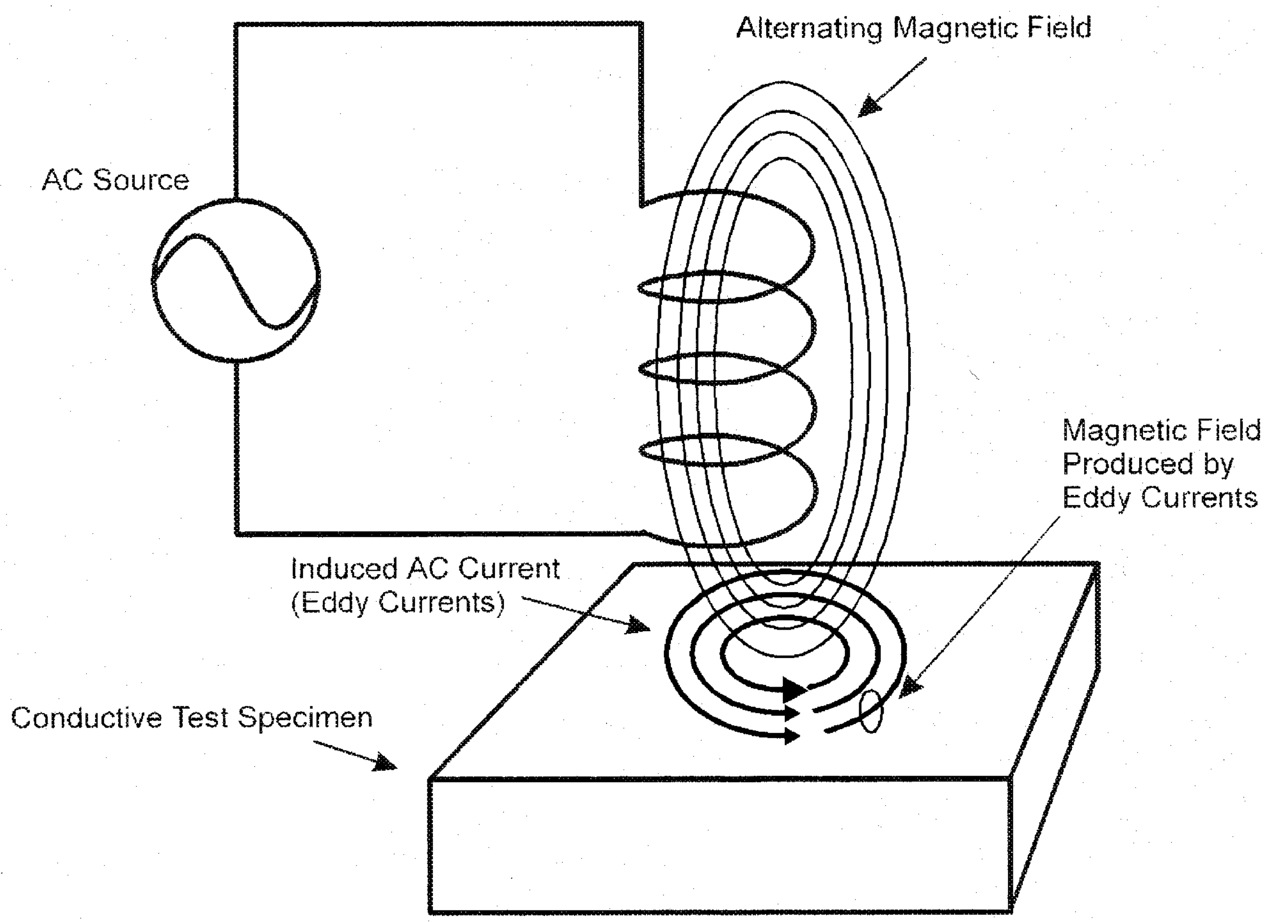
- Applicable to many components
- Radiological controls limit usefulness during intensive plant outage activities
  - Have to evacuate the area, disrupts other work
- Not sensitive to off-axis planar defects

Eddy current examination (ET)

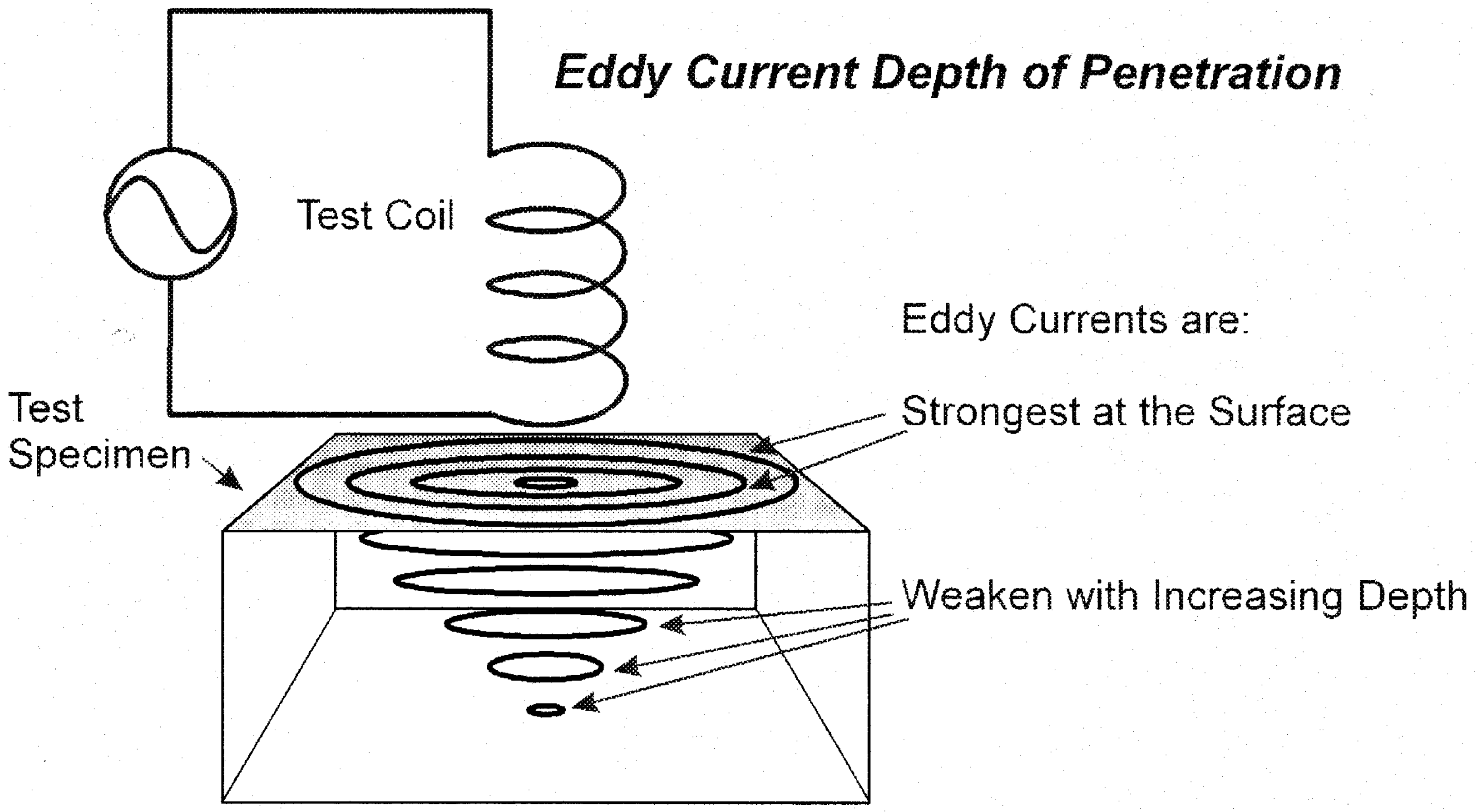
- Principle
  - Interaction of electromagnetic field with the material
  - Reveals surface and very near-surface features

Eddy Current

- Principle
  - Interaction of electromagnetic field with the material
  - Reveals surface and very near-surface features

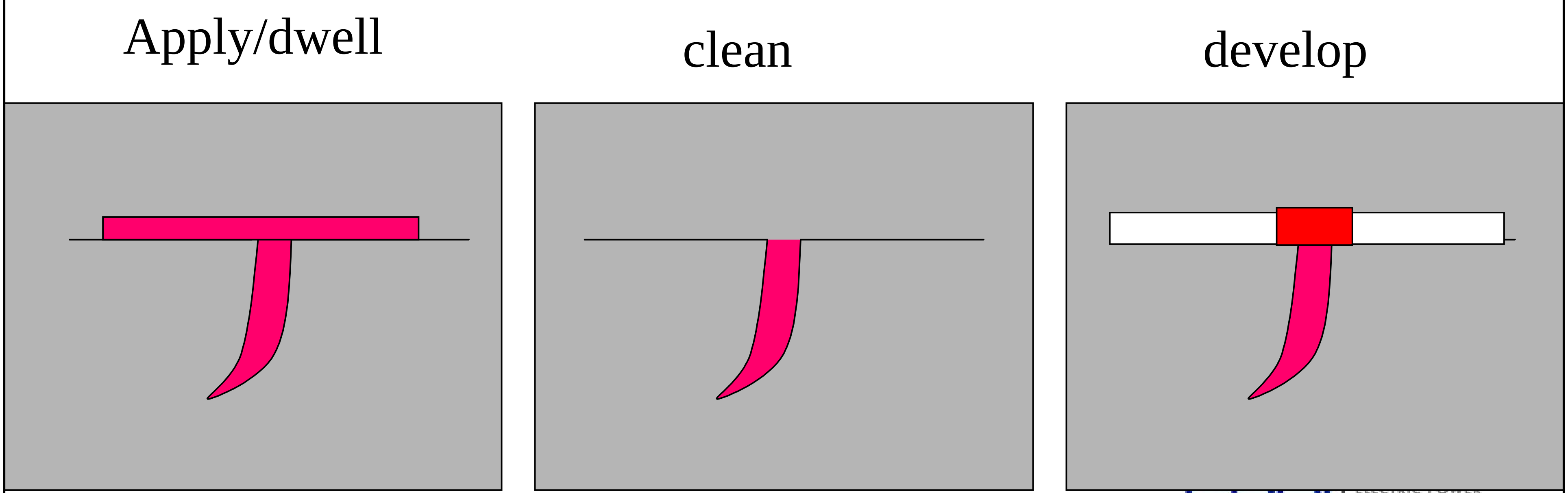


Eddy Current Principles



Liquid penetrant examination (PT)

- Principle
  - Indicator liquid (essentially, bright-red WD-40) drawn into surface breaking discontinuities by capillary action
  - Indications revealed by developer (chalky spray)
  - Strictly a surface examination method



Uncertainties

- Not all flaws that may be present will be detected
- location and sizing errors
- human errors
- NDE is only one part of the structural integrity picture
  - material properties
  - loads
  - environment

Other Reading

- Nondestructive Testing Handbook, ASNT, ISBN 0-931403-02-2
- ASM Handbook, Volume 17-Nondestructive Testing and Quality control, ISBN 0-87170-007-7
- Introduction to Phased Array Ultrasonic Technology Applications, RD Tech, Inc. ISBN 0-9735933-0-X
- Engineering Applications of Ultrasonic Time-of-flight Diffraction, JP Charlesworth and J.A.G. Temple, ISBN 0-86380-085-8

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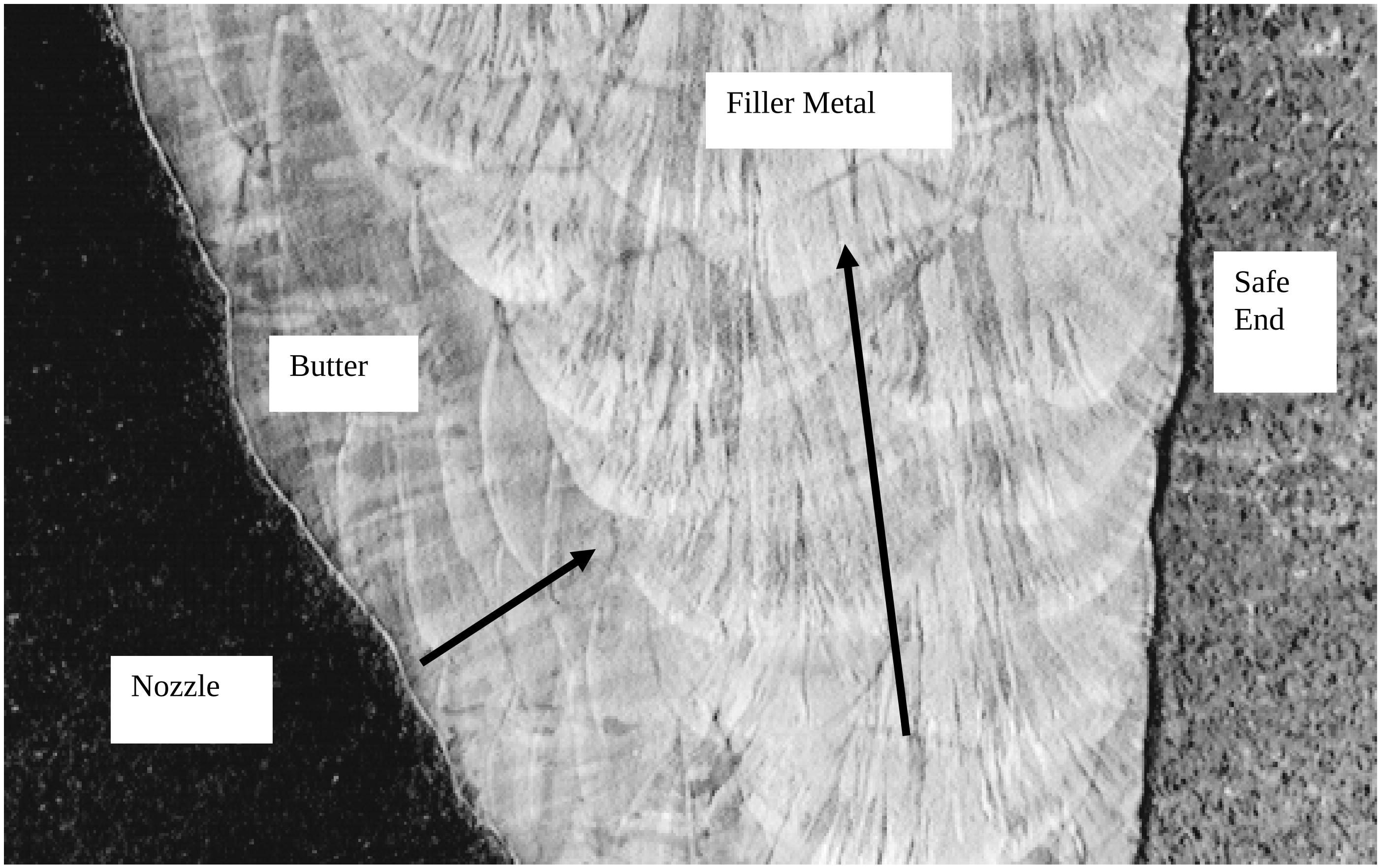
NDE of Stainless & Nickel Based Components

- Piping
  - Wrought and cast
  - Welds
  - Fittings
    - Elbows, Tees, etc
- Pump & valve bodies
- Vessel cladding & internals
- Vessel penetrations
- Steam generator and other heat exchanger tubing

UT of Stainless Steel and Nickel-based alloys

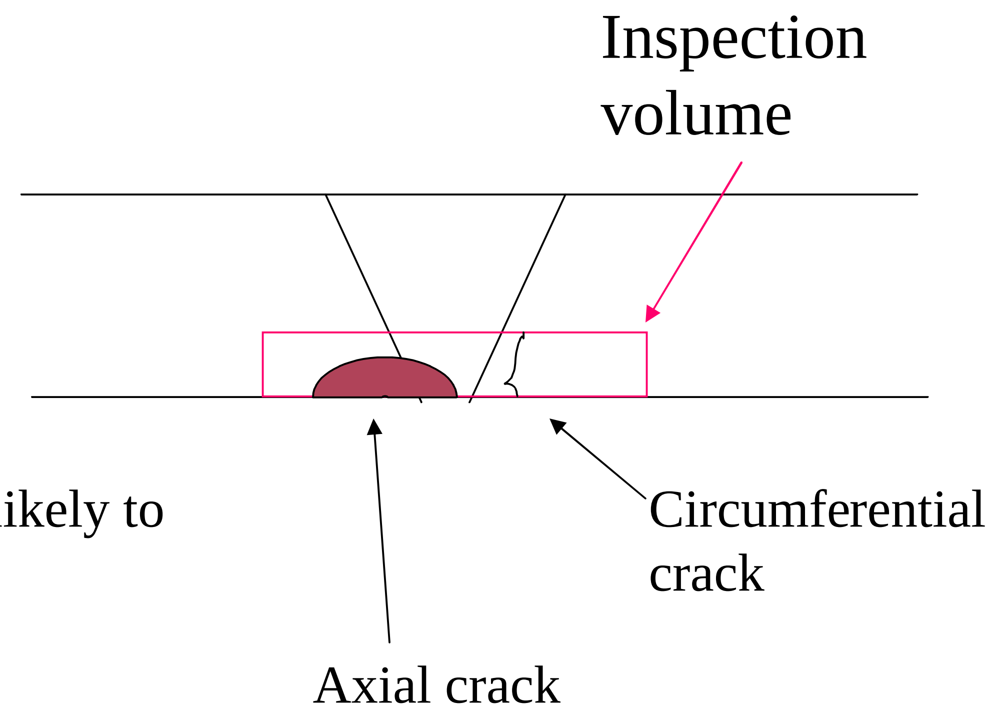
- UT is used extensively for volumetric inspection of SS & Ni based based piping welds
- Austenitic welds are acoustically anisotropic
  - Acoustic velocity is a function of beam direction with respect to the crystallographic orientation
- Each grain boundary is an impedance mismatch which causes
  - Attenuation (sensitivity loss)
  - Scattering
    - Noise
    - False calls
    - Interpretation errors
  - Re-direction of the beam can cause location errors and gaps in coverage

Dendritic Grain Structures in a Dissimilar Metal Weld



Piping Weld NDE

- Volumetric examination



Degradation mechanisms are most likely to initiate from the inside surface

- Stress corrosion cracking
- Flow assisted corrosion (FAC)
- Fatigue cracking
- Must consider the potential for axial or circumferential cracking

Intergranular stress corrosion cracking (IGSCC)

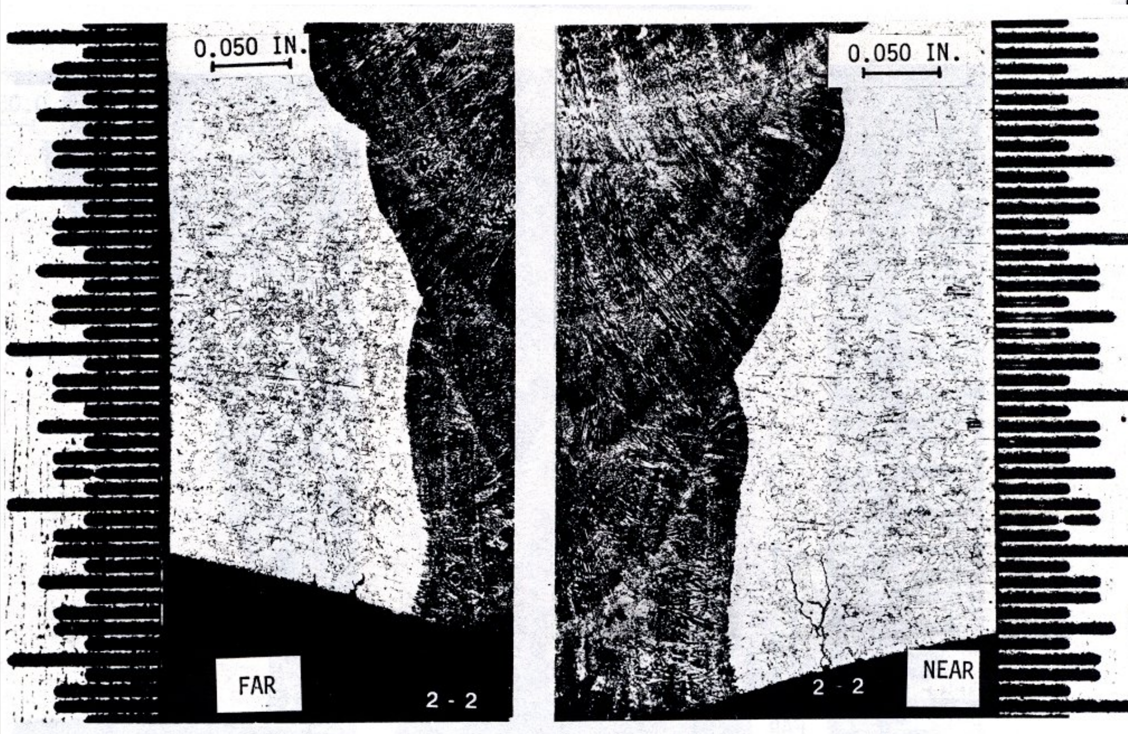
- Typically found in BWR SS piping welds and RPv internals sensitized to SCC
- Primary location is weld heat affected zone (HAZ)
  - Crack typically starts near the weld root
  - Progresses through the wall following the HAZ

BWR Recirculation Piping-IGSCC

Typical IGSCC found in stainless steel BWR recirculation system piping

•Located in Heat Affected Zone of base metal

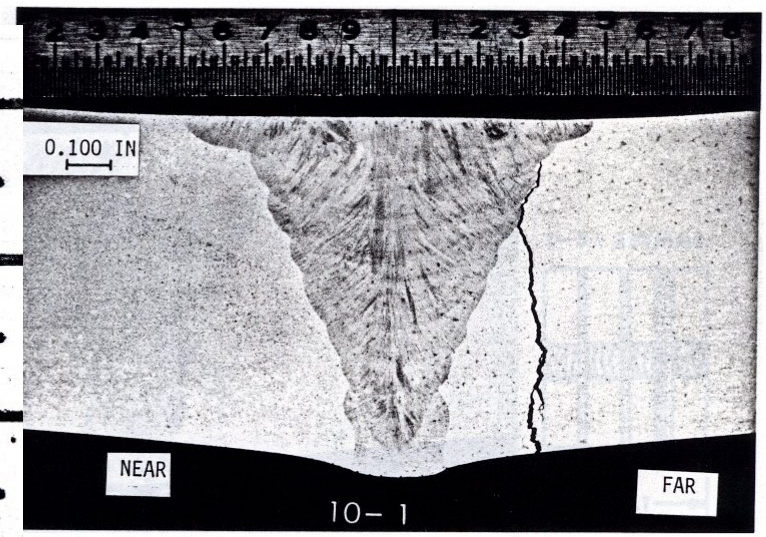
•Branched



Example of deep cracking

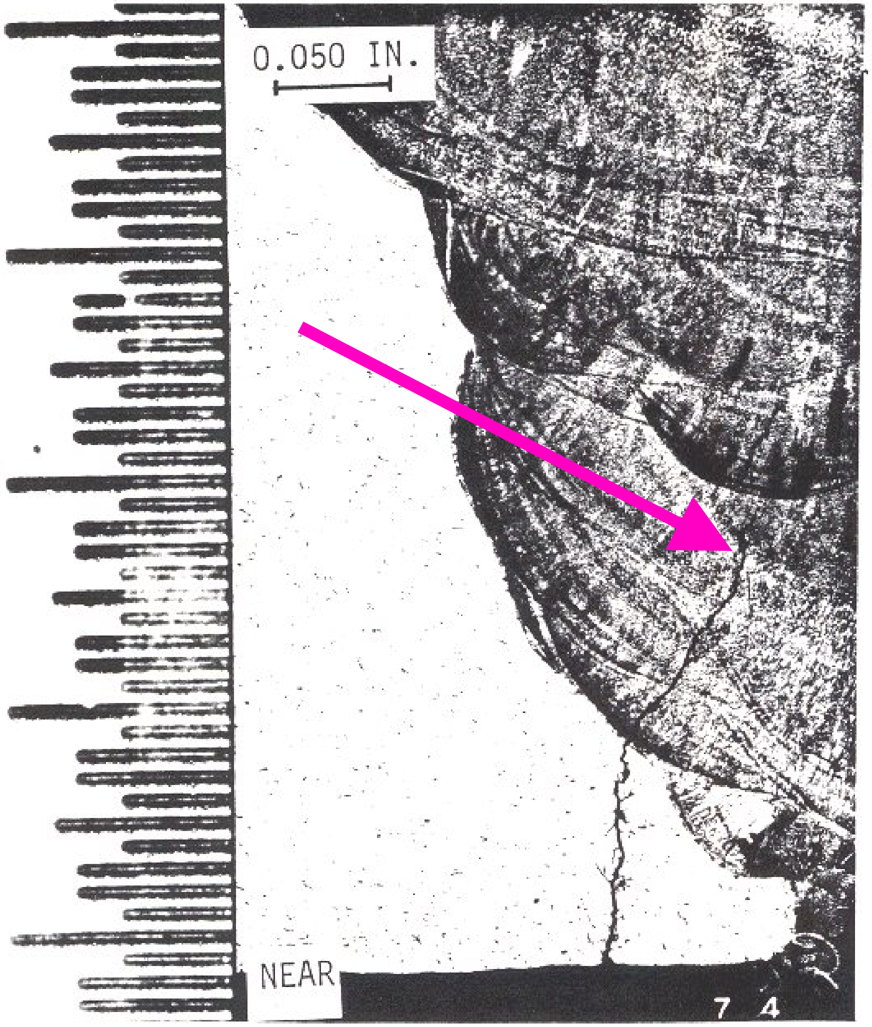
•Grows toward weld

•Usually follows weld profile after reaching the weld



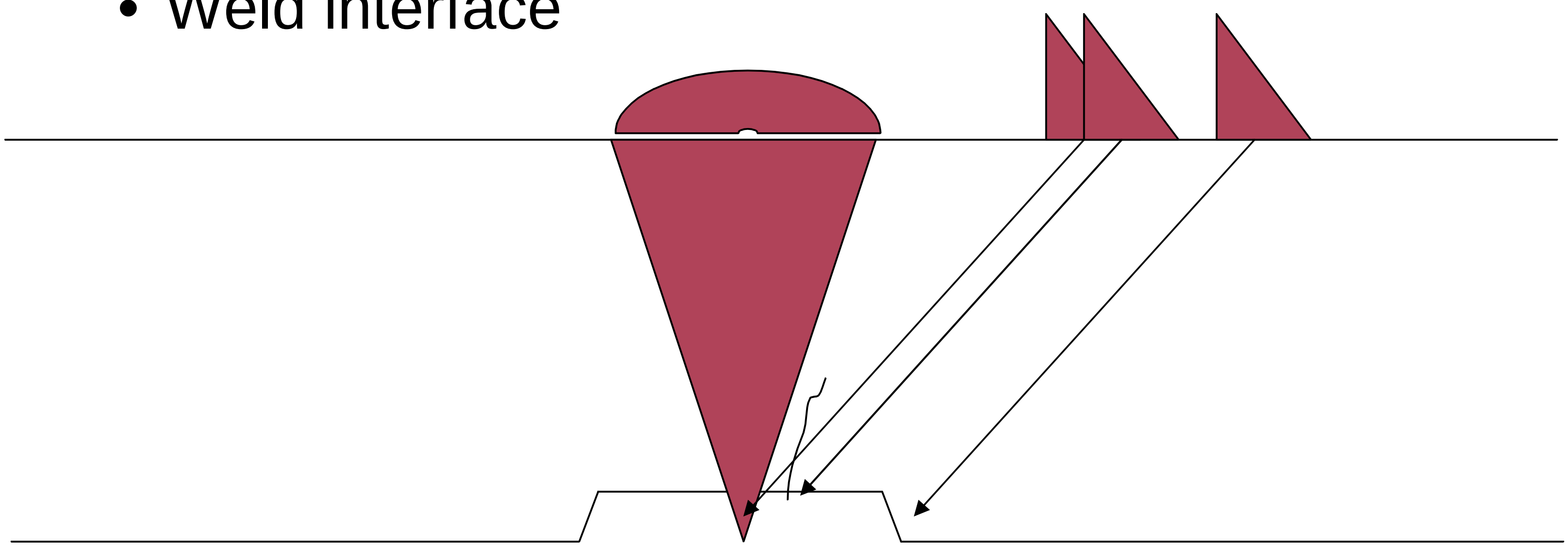
BWR Recirculation Piping-IGSCC

Example of crack growing into weld



IGSCC Discrimination
Root, Flaw, Counterbore

- UT crack detection
  - Identification of the crack signal is challenging when there are other competing signals
    - Weld root
    - Counterbore
    - Weld interface



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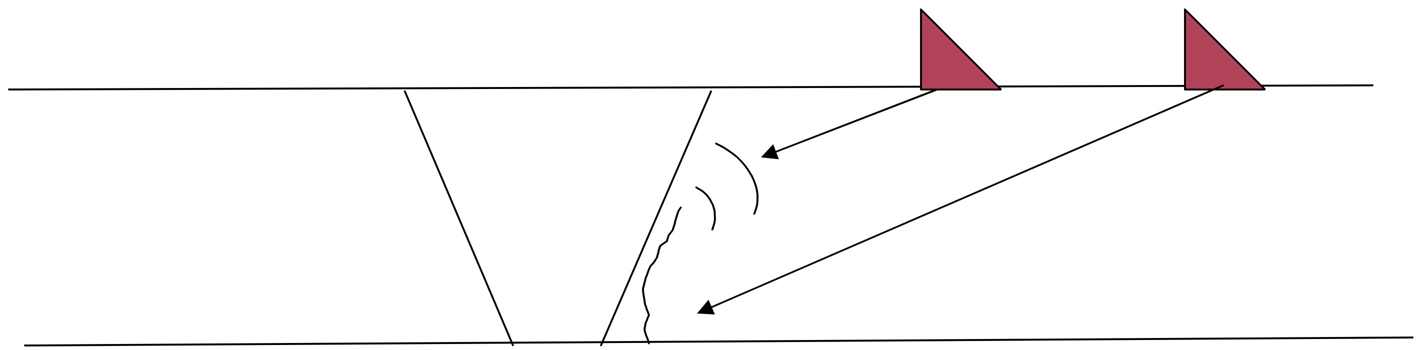
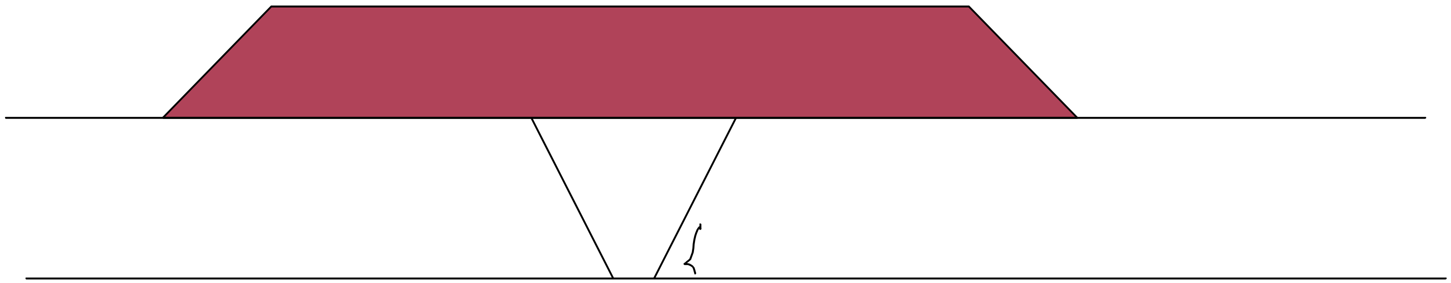
IGSCC

- Sizing is very challenging
  - Locating a diffracted wave from the crack tip
  - Difference in time-of-flight between the crack base and crack tip is used to calculate the depth
  - Experience needed to identify the tip signal



Overlay Repair

- Application of weld overlay is an effective repair method for cracked piping
  - Restores full structural integrity to a cracked pipe
  - Prevents further crack initiation and growth
- Requires good inspection after application, and continued monitoring
  - Verify integrity of the overlay itself
  - Monitor to ensure no growth of original cracks



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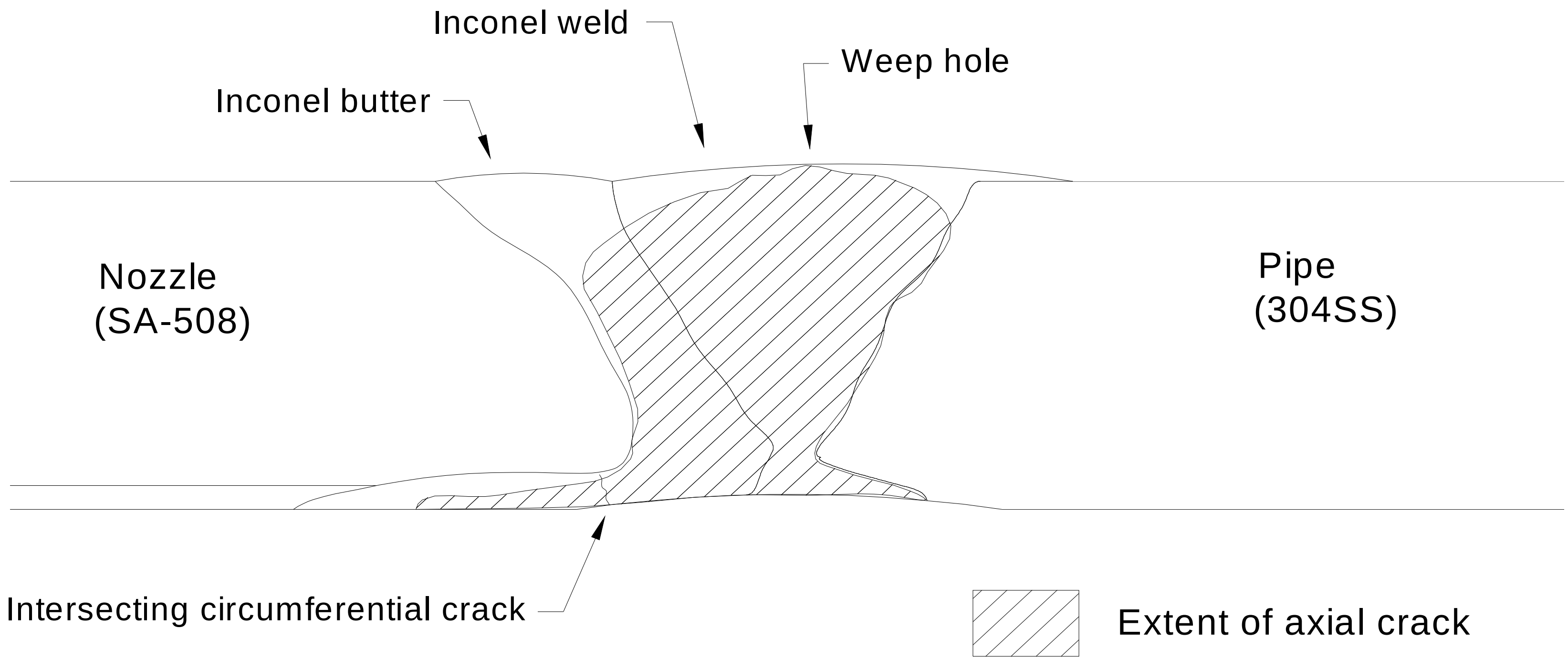
Primary water stress corrosion cracking (PWSCC) in PWR Units

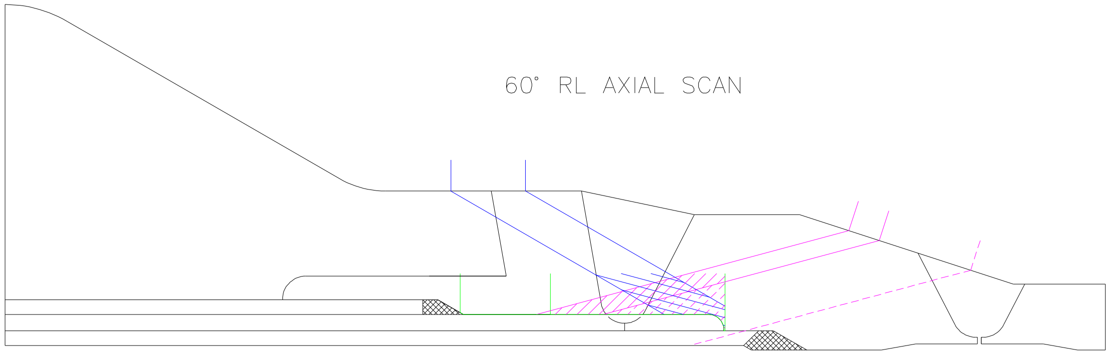
- PWSCC has been found in PWR main coolant systems with Alloy 600/182/82
- Alloy 182 welds
  - Dissimilar metal (DM) piping welds
  - Vessel head penetrations
- Alloy 600
  - Steam generator tubing

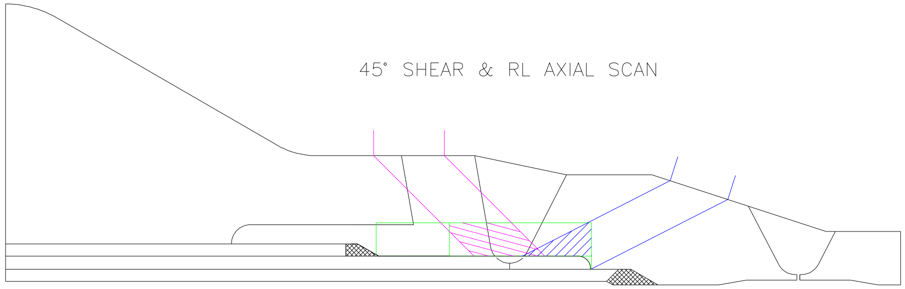
PWSCC in PWR Nozzle-Safe End Dissimilar Metal Weld at VC Summer Plant



Examination of Dissimilar Metal Welds

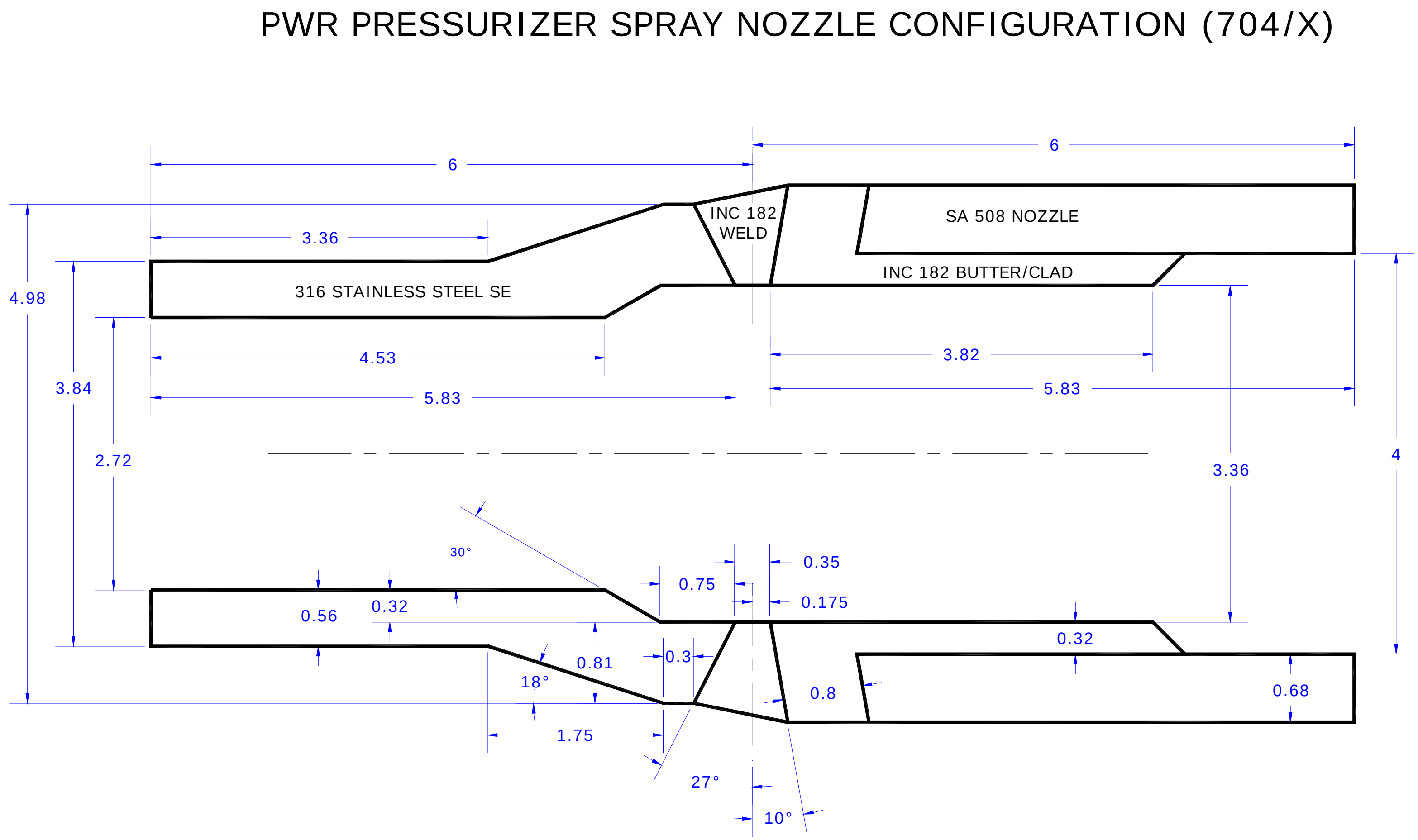
Pressurizer Spray/Relief nozzles



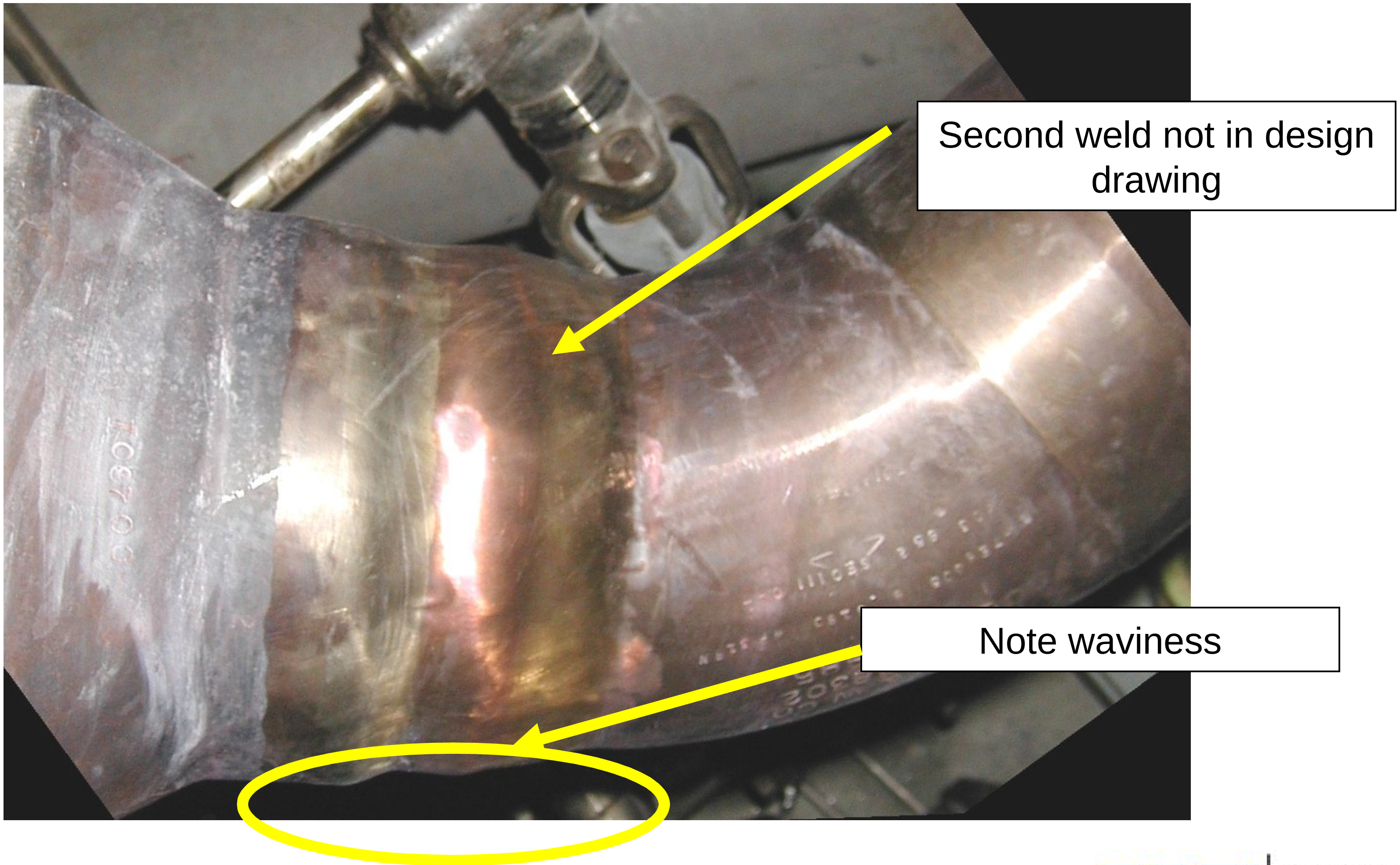


Must use a combination of probe angles and scanning surfaces to obtain coverage of the examination volume-may not get all of it

Design Drawings can't be trusted



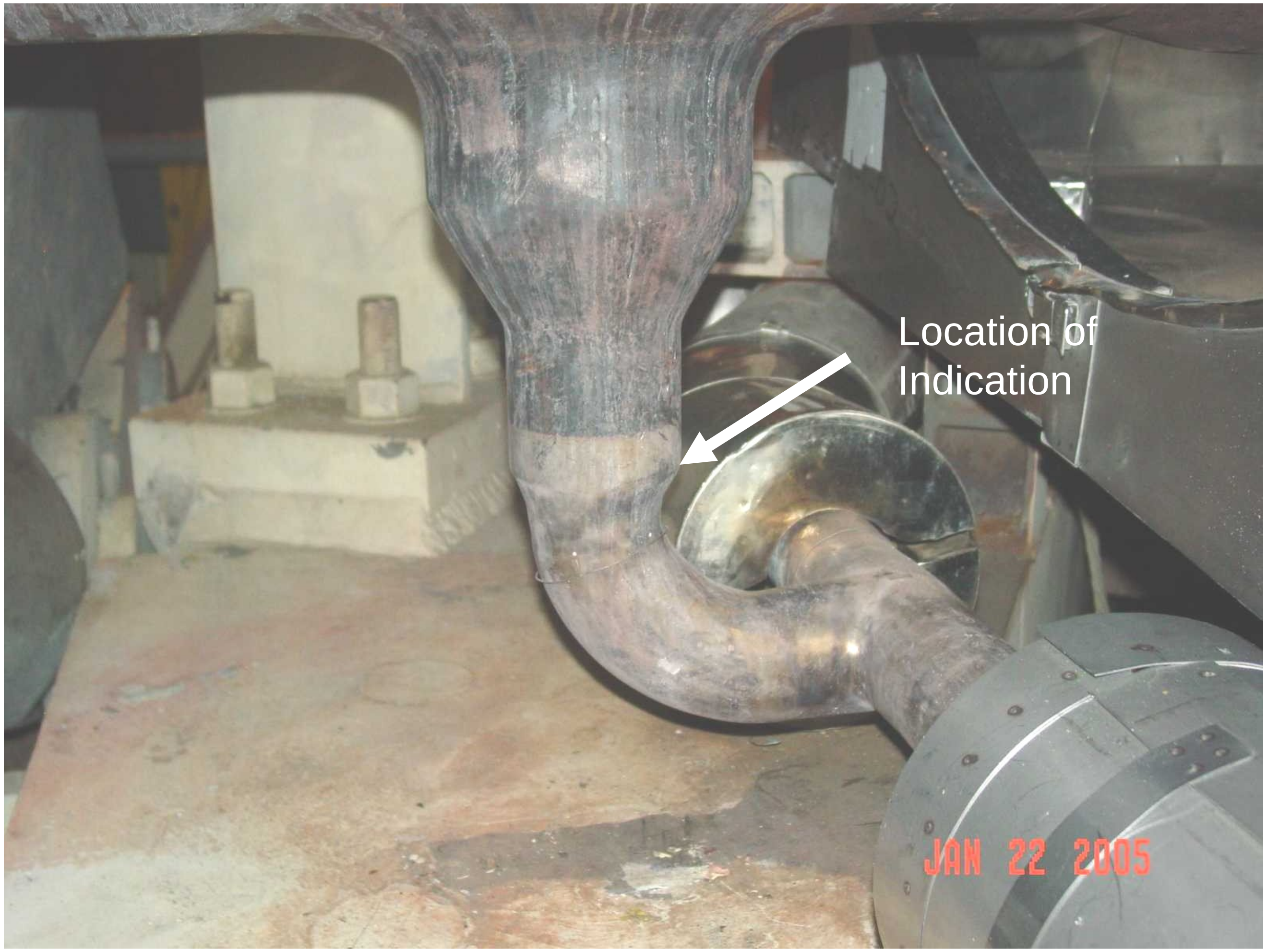
Actual Configuration



Example of a PWSCC Issue

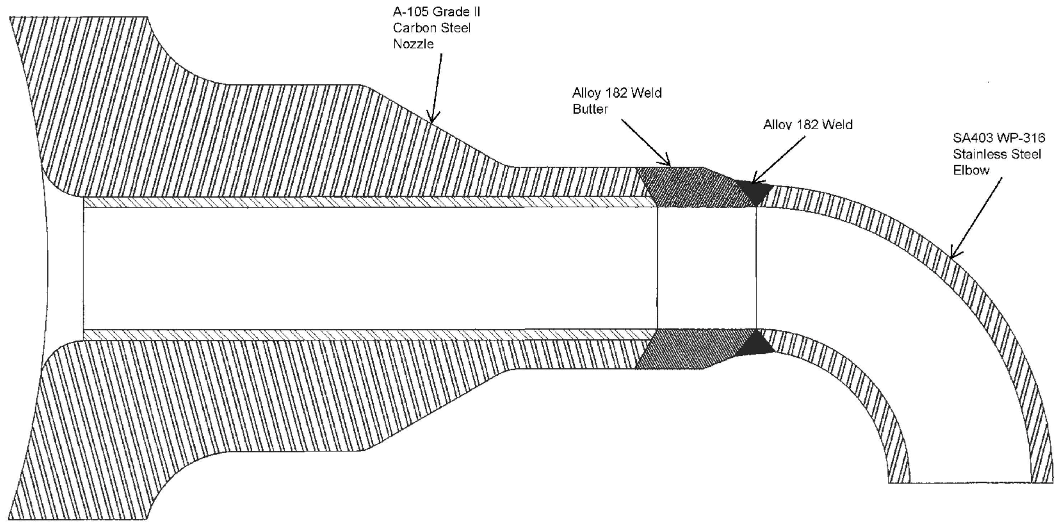
- Indication detected in a PWR cold leg drain line dissimilar metal weld
- Evaluated as a defect
- Overlay repair designed and installed

RCP 1-1 Cold Leg Drain

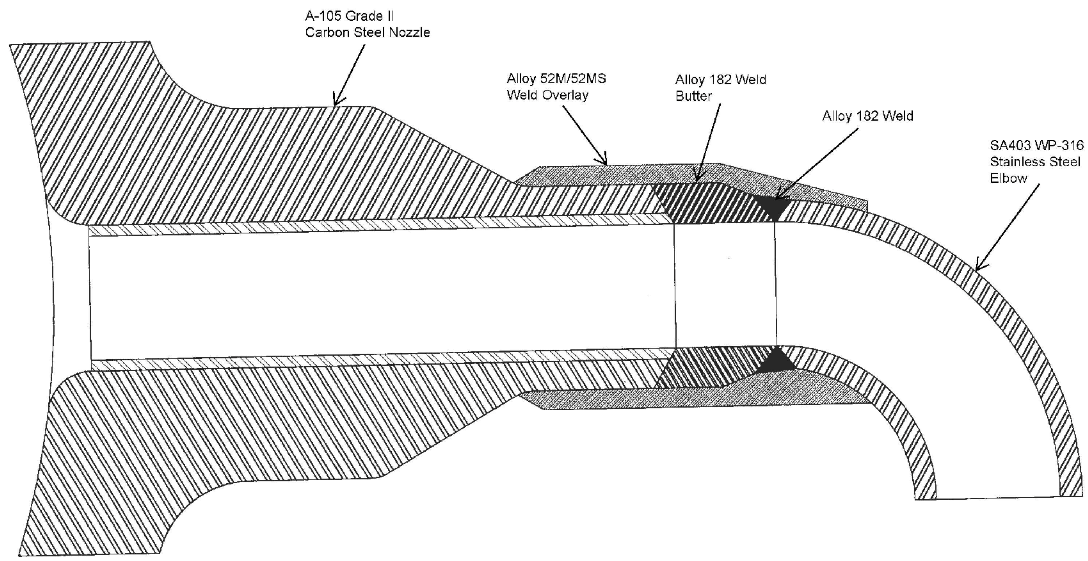


RCP 1-1 Cold Leg Drain

As-built configuration



Overlay configuration



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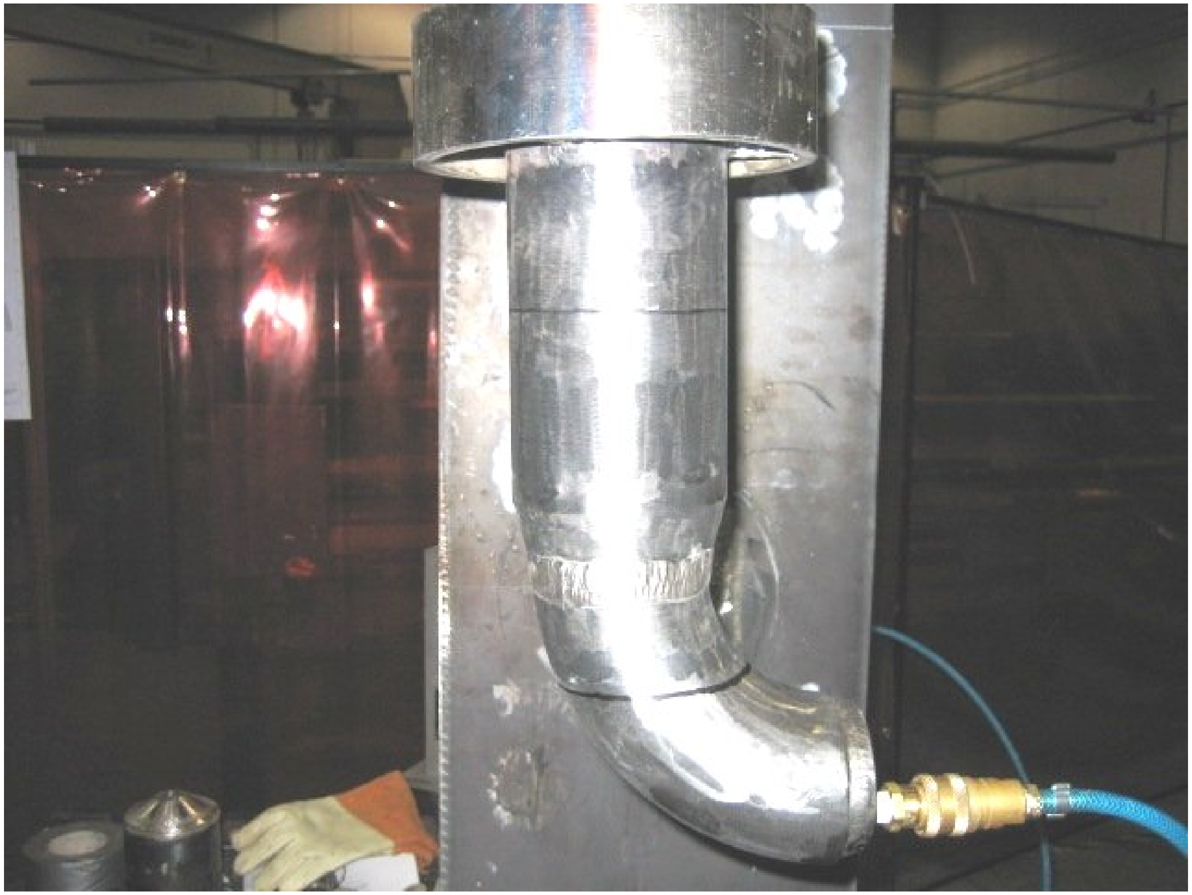

Mockup for Welding Proof of Principle
WSI Norcross, GA

RCP 1-1 Cold Leg Drain

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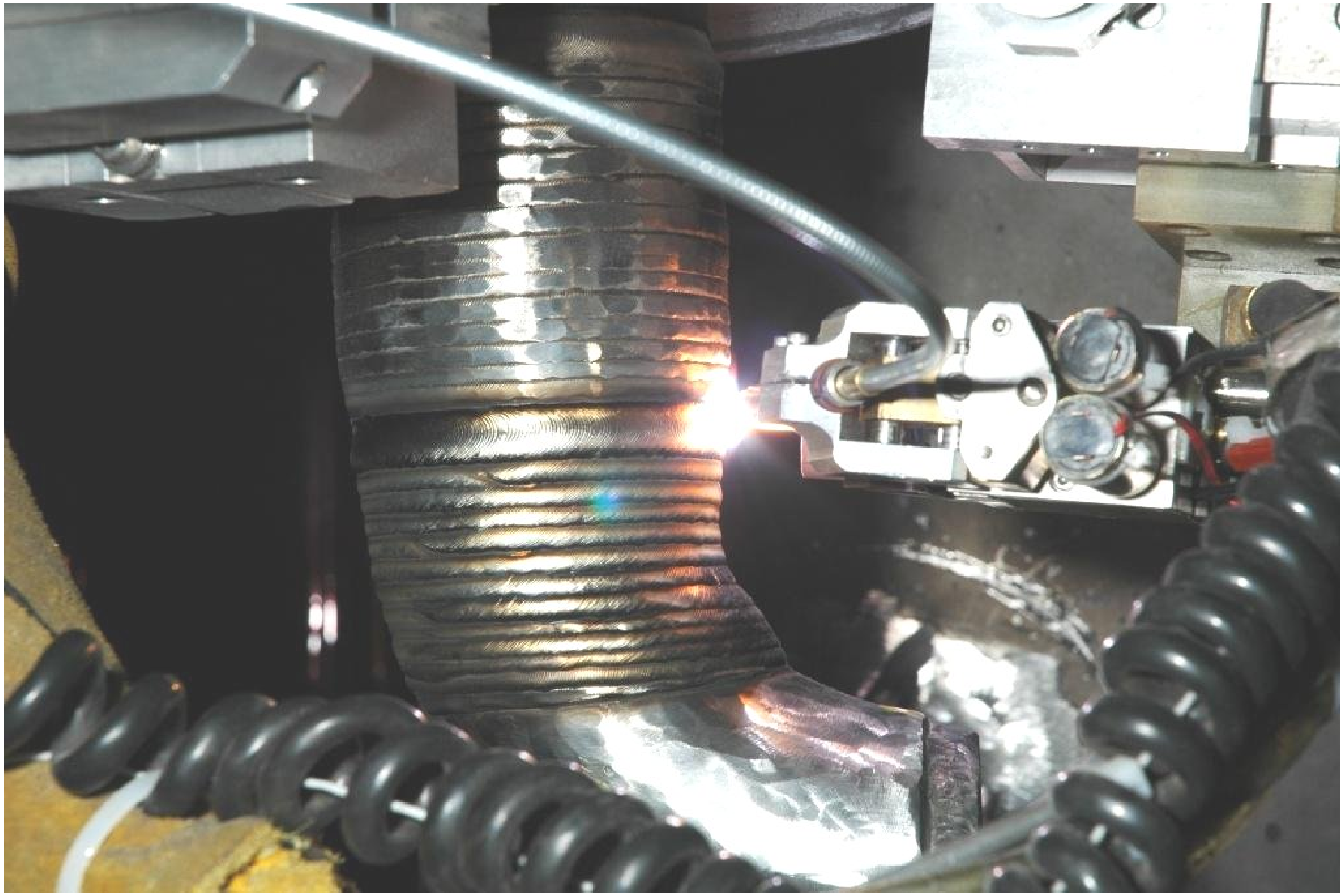

Mockup for Welding Proof of Principle
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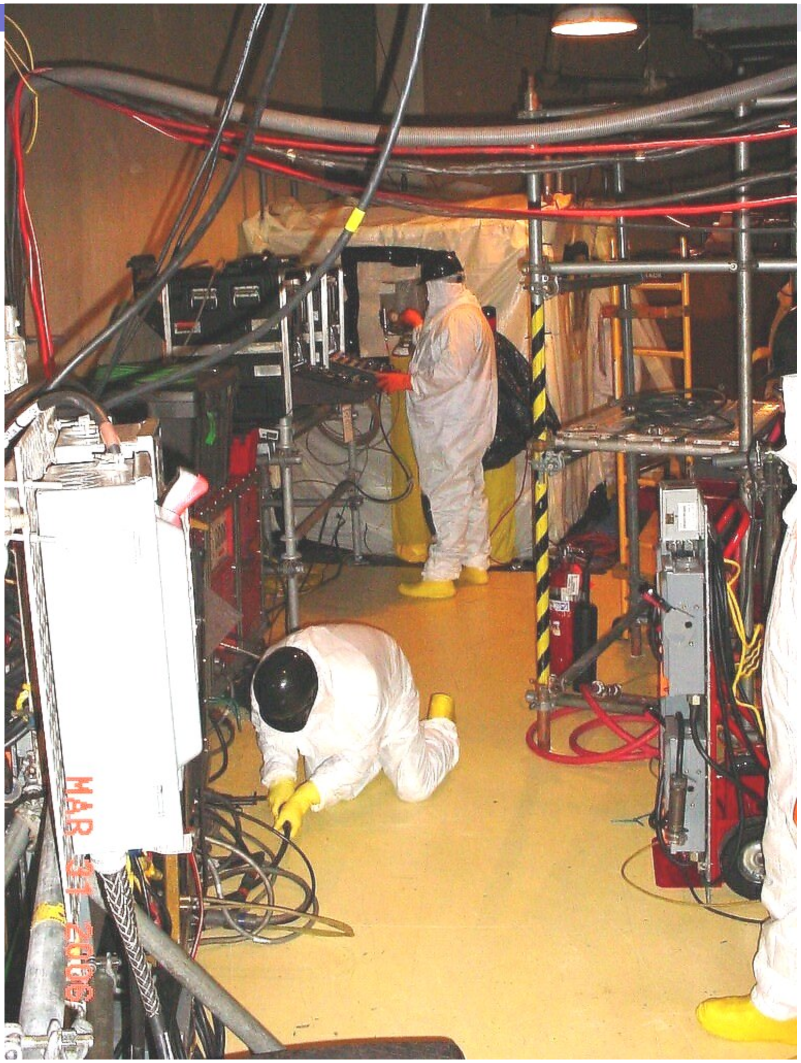
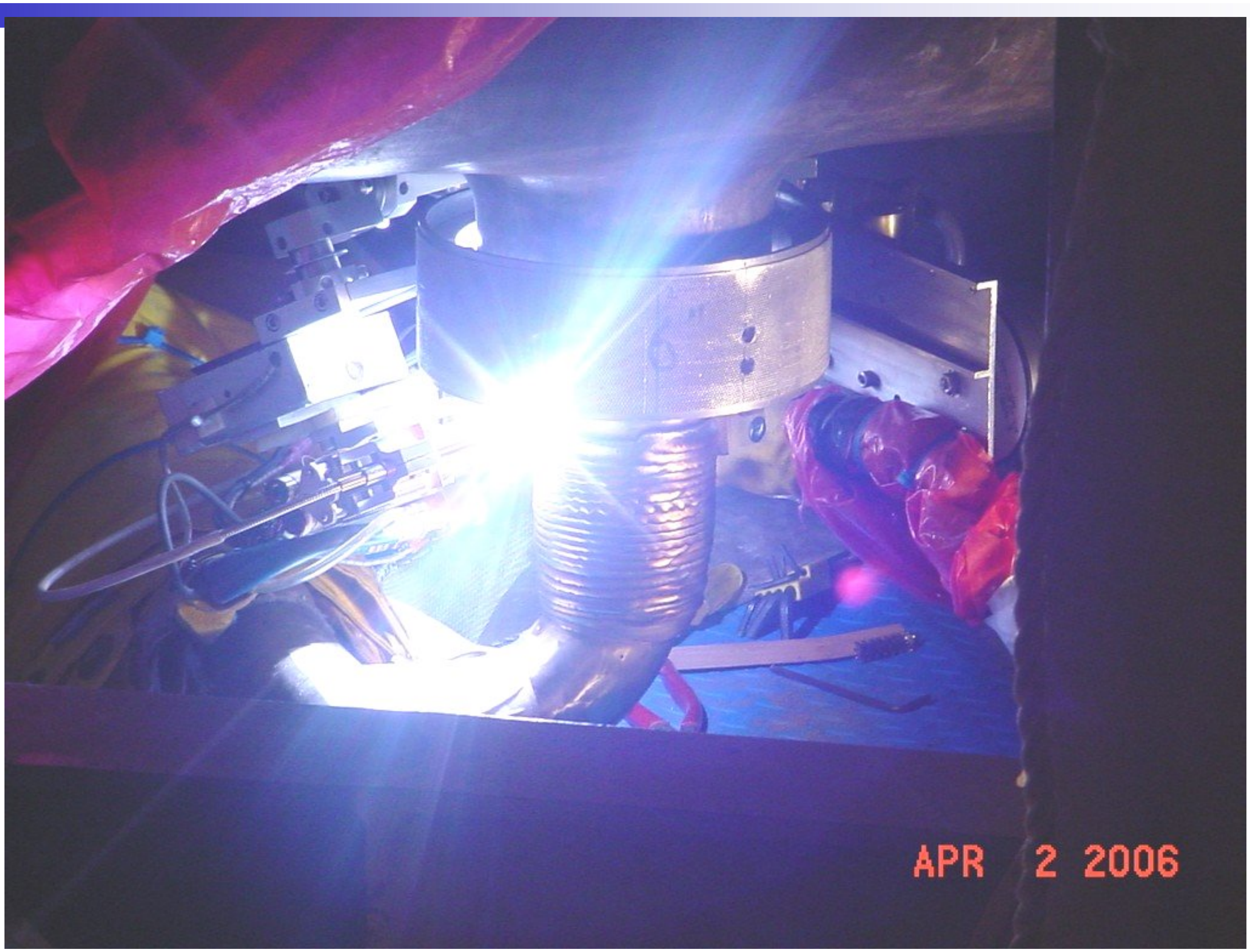


WSI Welding Power & Controls Setup

RCP 1-1 Cold Leg Drain

WSI Remote Welding Operation

RCP 1-1 Cold Leg Drain



Welding the Overlay – Day 15 After Indication Discovery

RCP 1-1 Cold Leg Drain

Final UT'd Overlay – 16 Days 6 Hours After Indication Discovery

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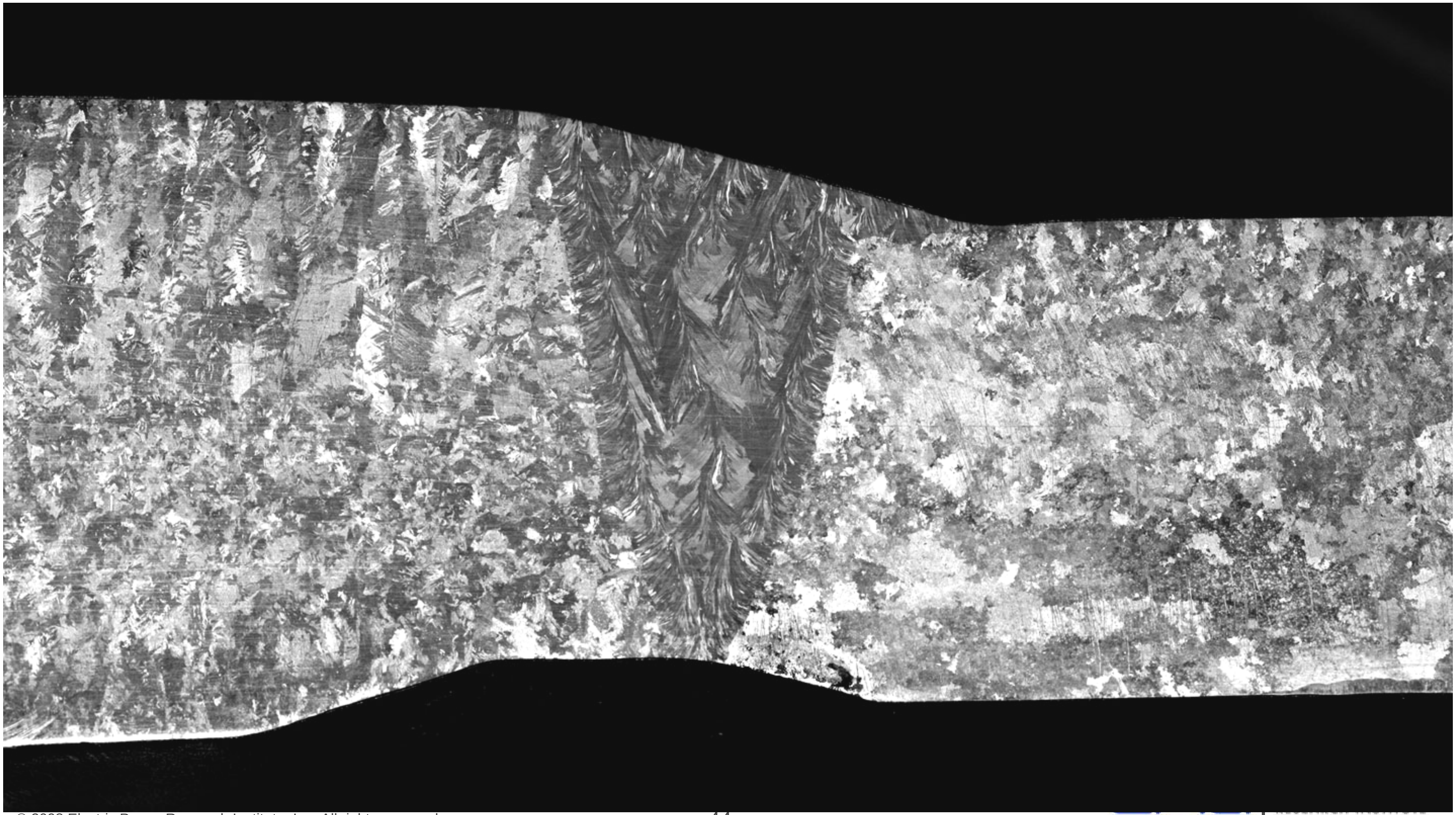
Cast Stainless Steel

- Some components are stainless steel castings
  - Pump and valve bodies, piping elbows: statically cast
  - Piping: centrifugally cast
- Castings can have very large grains
- In stainless steel, this makes UT extremely difficult because the grains are acoustically anisotropic
- Only very low-frequency sound can penetrate the metal
  - Poor resolution
  - Possibility of transmission through the face of a tight crack – no reflection, no detection
- Round-robin tests have shown that the UT capability is very poor (scanning on the outside, to detect cracking on the inside)

Cast Stainless Steel



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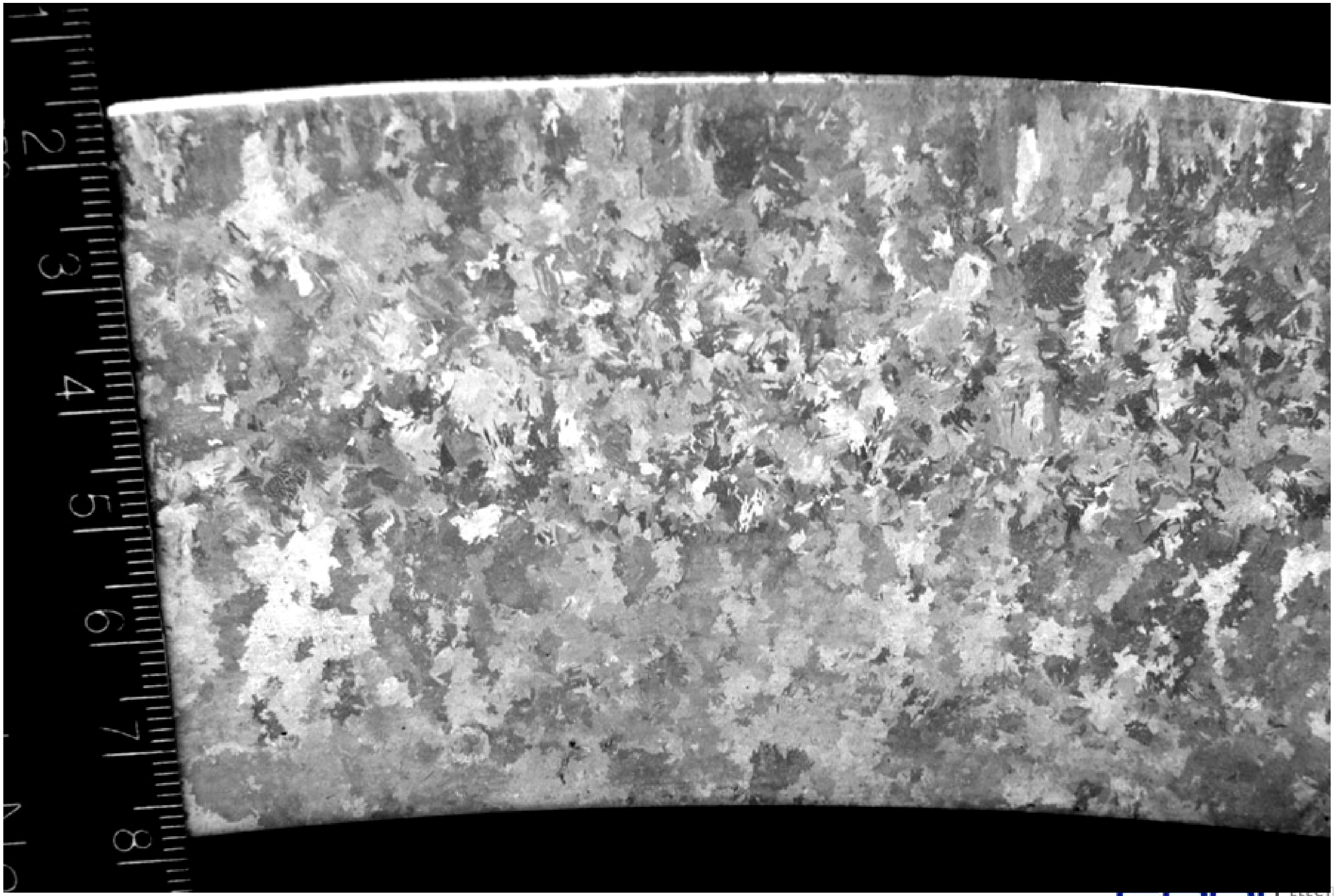

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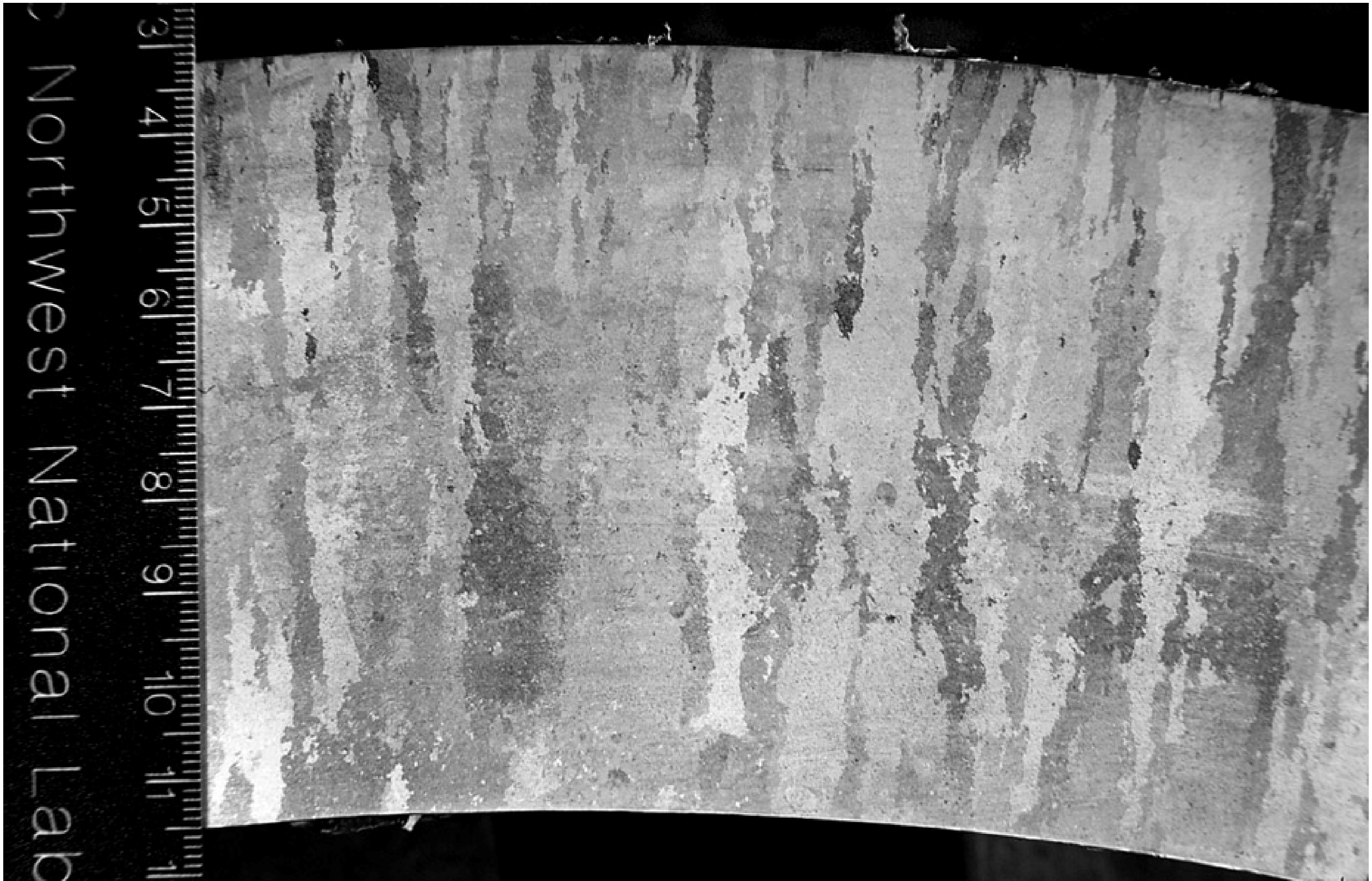

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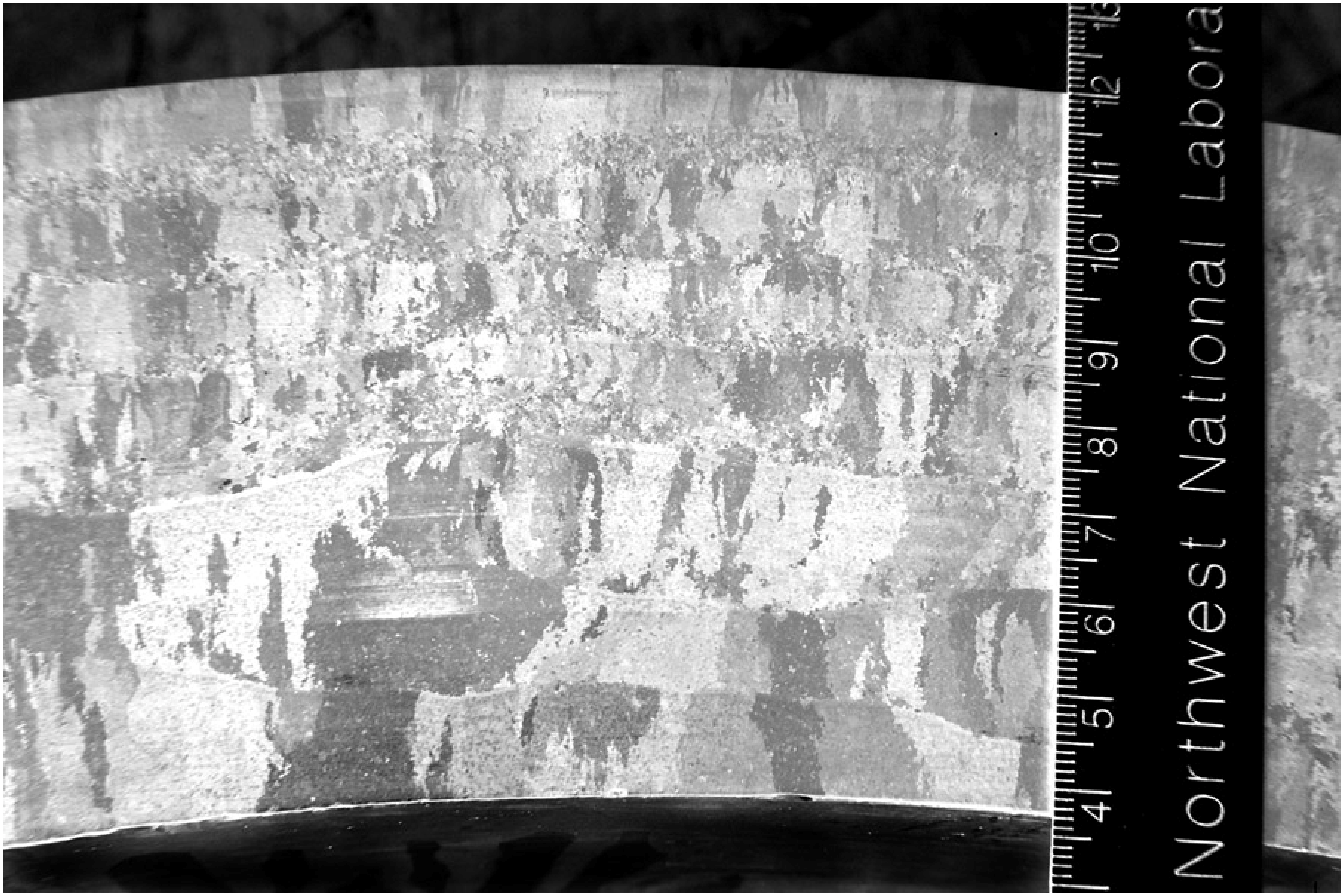

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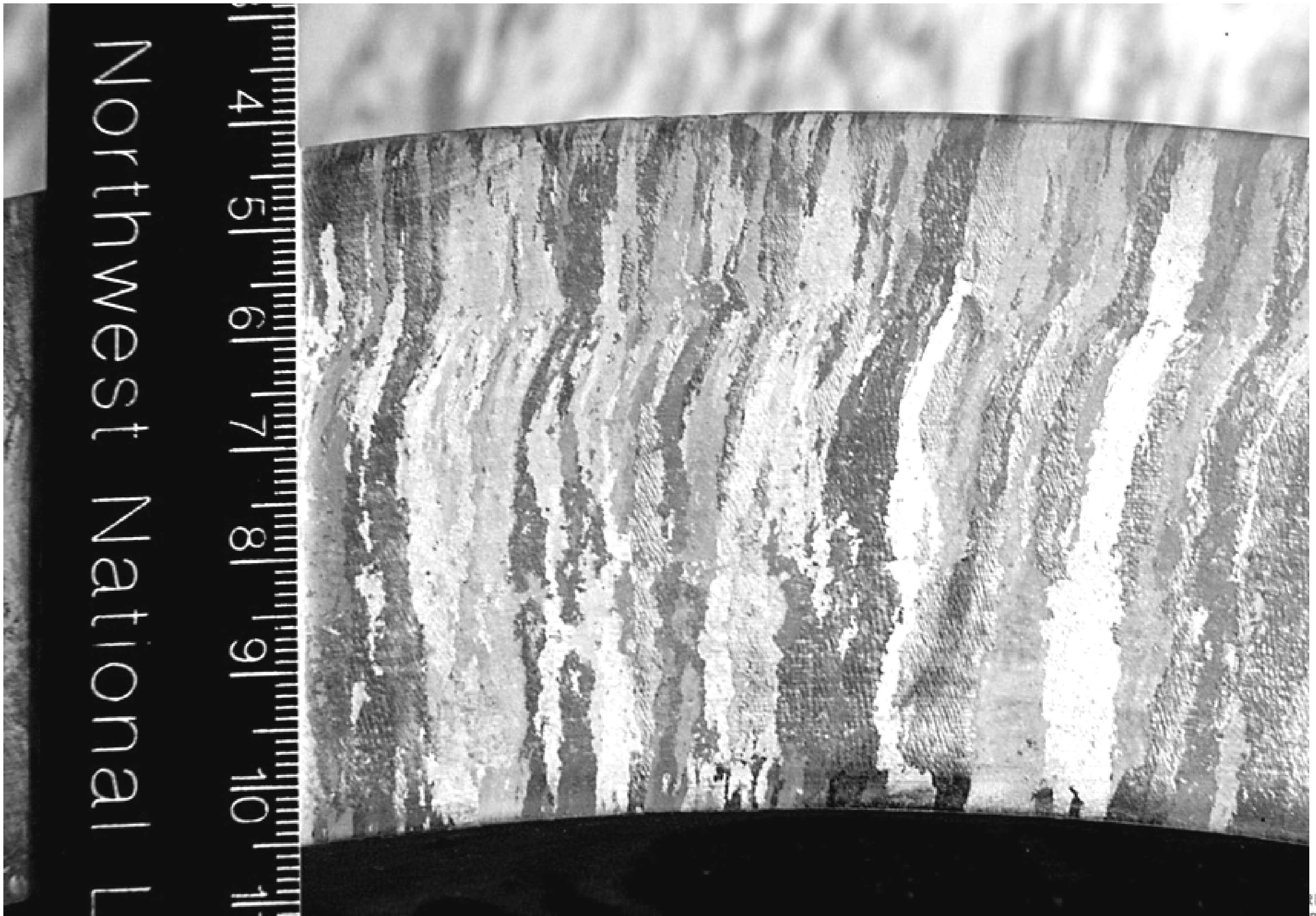
Cast Stainless Steel



Cast Stainless Steel

- No known degradation mechanism for CSS reactor coolant piping
  - No leaks
  - No failures
- No effective outside-surface UT technique is on the horizon
- Interest is growing
  - Thermal aging embrittlement
  - License renewal commitments
- Any significant effort to develop and qualify NDE will require fabrication of piping to use for mockups

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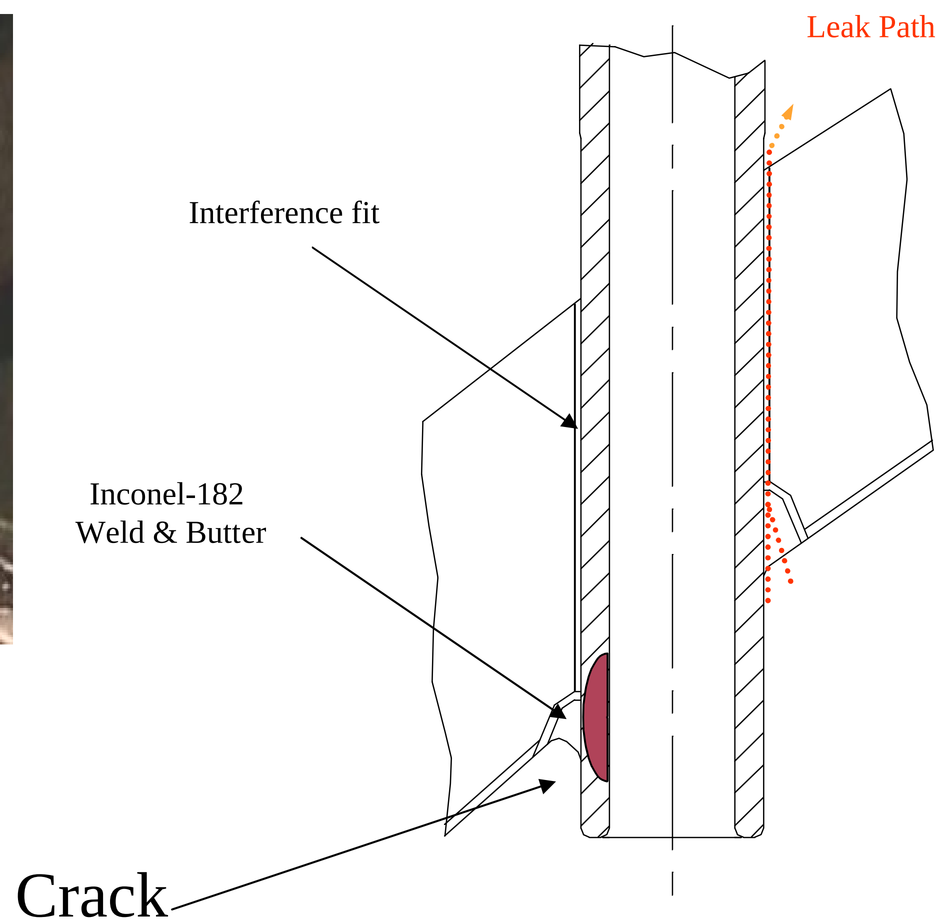
CRDM Penetration Leaks

Boric Acid deposits
on Top Head



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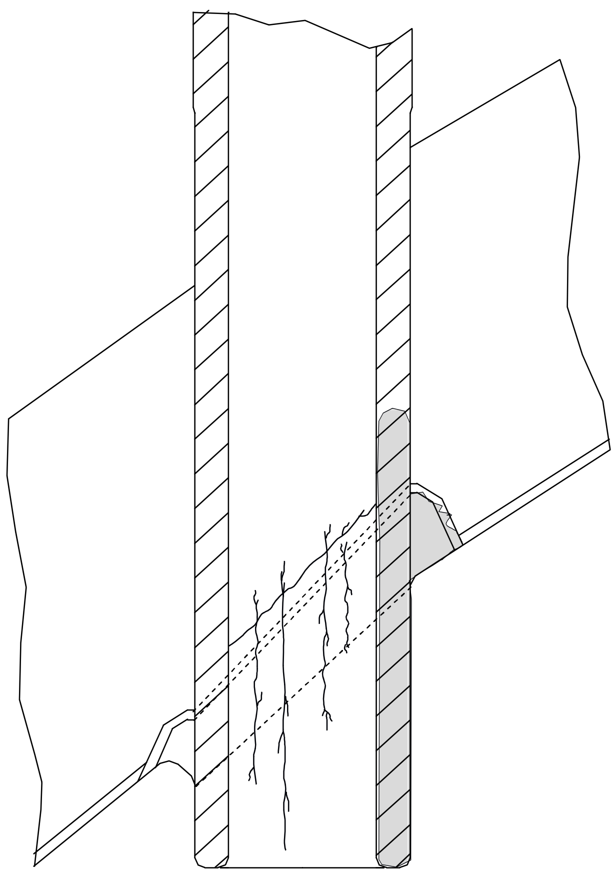
PWSCC in CRDM Penetrations



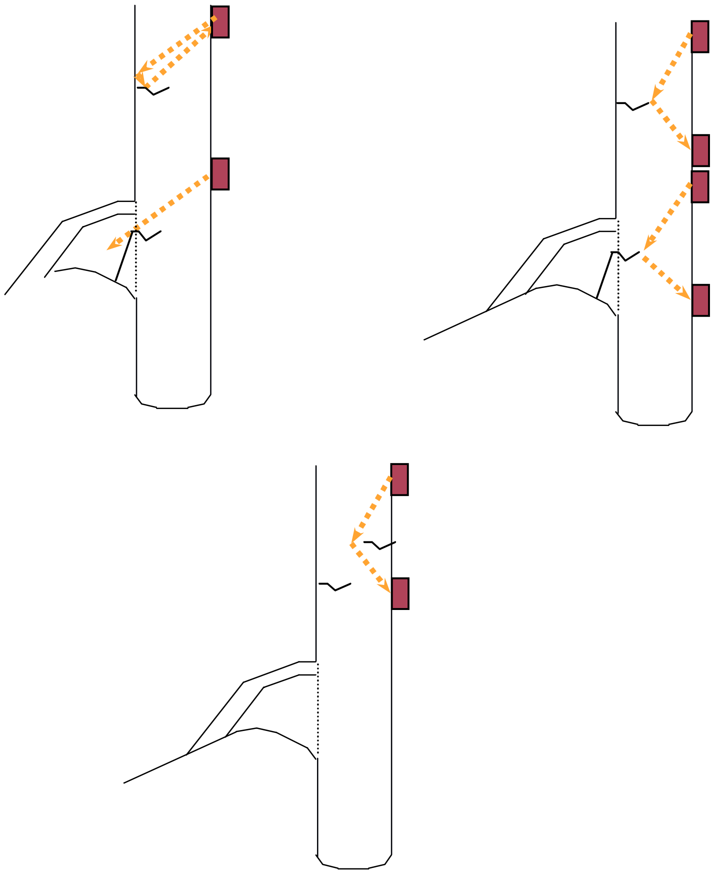
Base metal PWSCC

J-Groove weld cracking

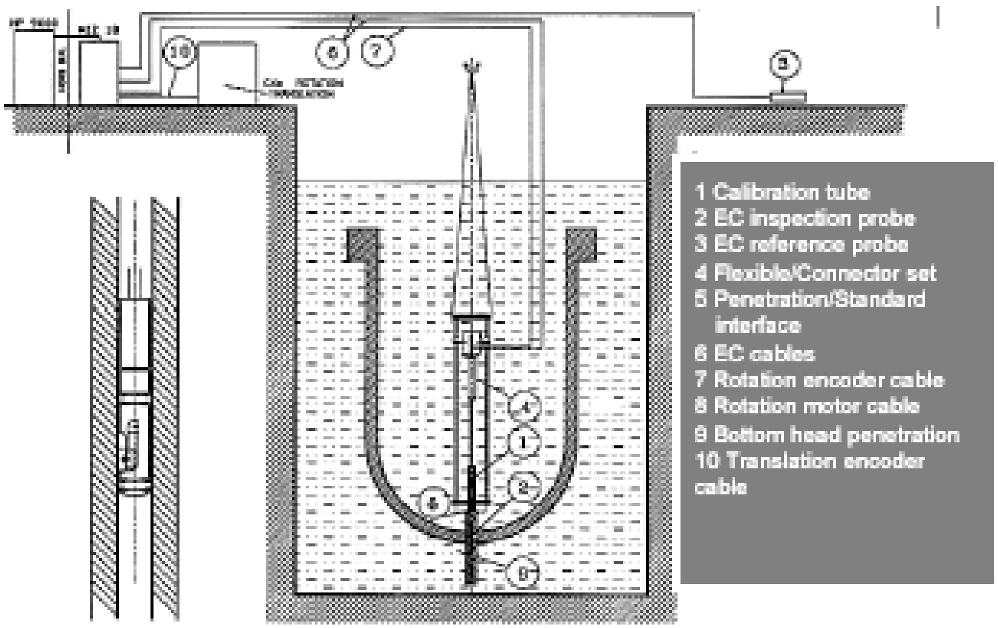
Evidence of Leakage

Inspection of Vessel Penetrations

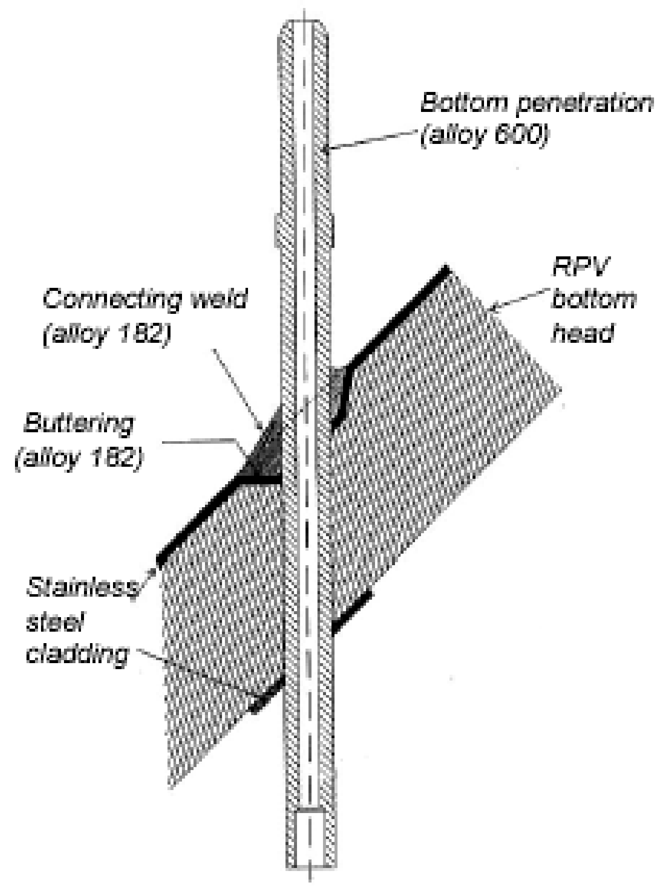
- UT used for detection and sizing
- ET is used in some cases for detection and length sizing
- ET used for surface examination of the wetted surfaces
- UT of the J-Groove weld has not been proven reliable-many sources of false calls



Bottom Mounted Instrumentation Penetrations



General Layout



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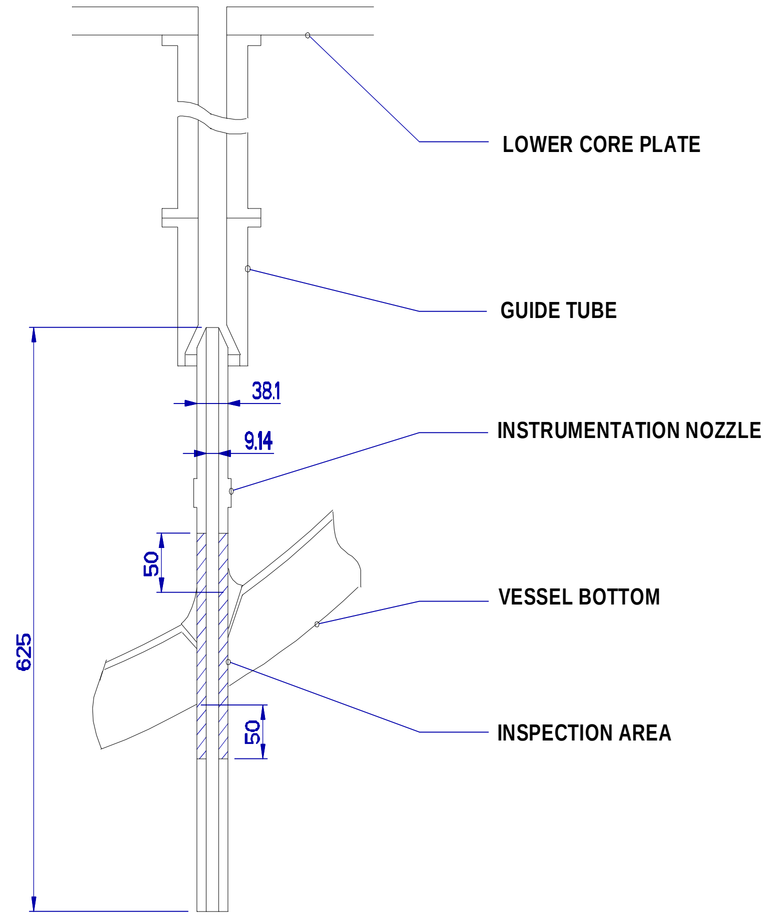
Bottom Mounted Instrumentation Penetrations

- Small amount of residue discovered on 2 BMI penetrations at South Texas Plant Unit 1
- Deposits confirmed to be boric acid from reactor coolant
- Very small amount of deposits- 150 mg and 3 mg

Bottom Mounted Instrumentation Penetrations

- Inspection approach under consideration
    - Volumetric examination of the tube
    - Surface examination of the J-groove weld
- Demonstration of techniques using mockups



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Summary

- Inspection of stainless steel and Nickel based materials presents challenges
  - Anisotropy
  - Geometry
  - Access
  - High radiation areas
- Many of these problems can be overcome with proper advance knowledge of the configurations
  - Allow time for planning, training, and qualification of the process
- Gaps in the NDE technology remain
  - Welds with excessively wavy surfaces
  - Cast stainless steel
  - Volumetric examination of the J-groove welds in vessel head penetrations

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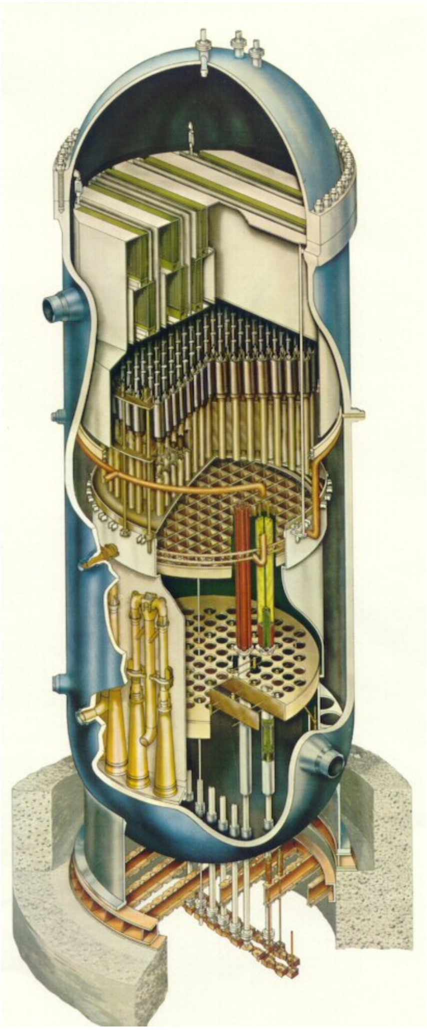
Pressure Vessel Inspection

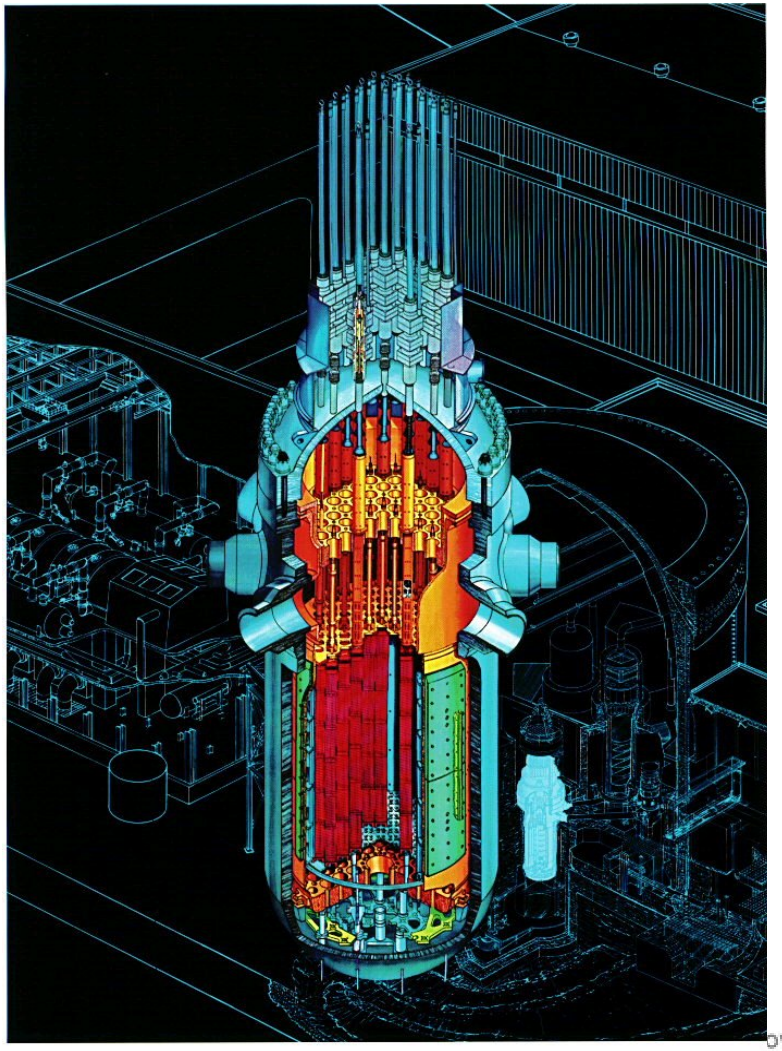
- Overview
  - Failure of the Reactor Pressure Vessel (RPV) cannot be considered a credible event
  - Highest standards for design, fabrication, operation, inspection
  - Service experience has been very good
    - No inservice flaws in the vessel shell

NDE of Pressure Vessels: Practical considerations

- High safety significance
- Thick sections, sometimes complex geometry
- Difficult access
  - Inspection from inside surface must be performed using remote, automated equipment
  - Inspection from outside has poor access and high radiation levels
    - Mostly performed using automated equipment
    - Specific areas can be picked up using manual UT
- In-vessel time is precious; critical path is nominally worth $1M/day

BWR and PWR Vessel Cutaways

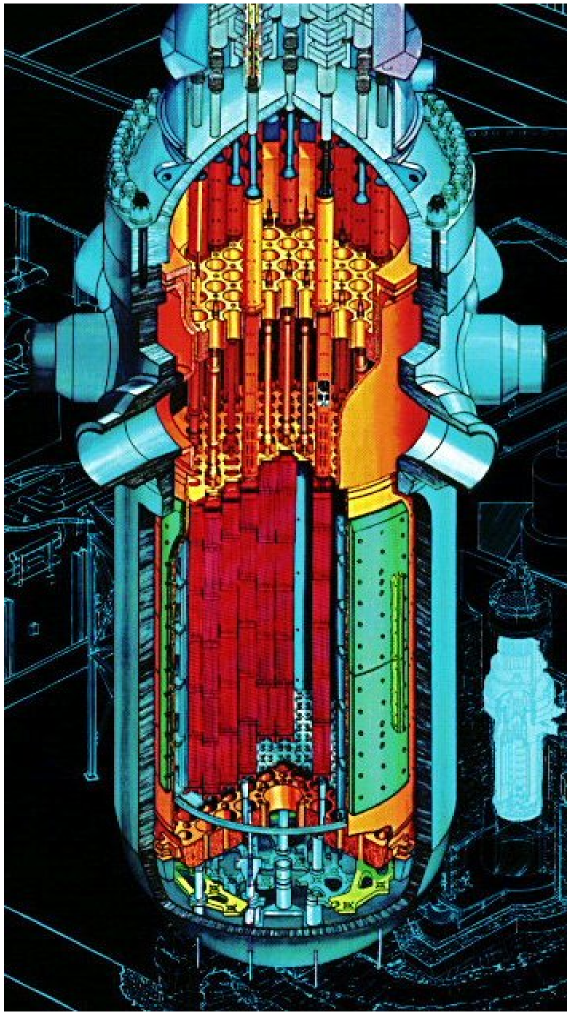




PWR Pressure Vessel

PWR vessels are examined from the inside surface after removal of internals

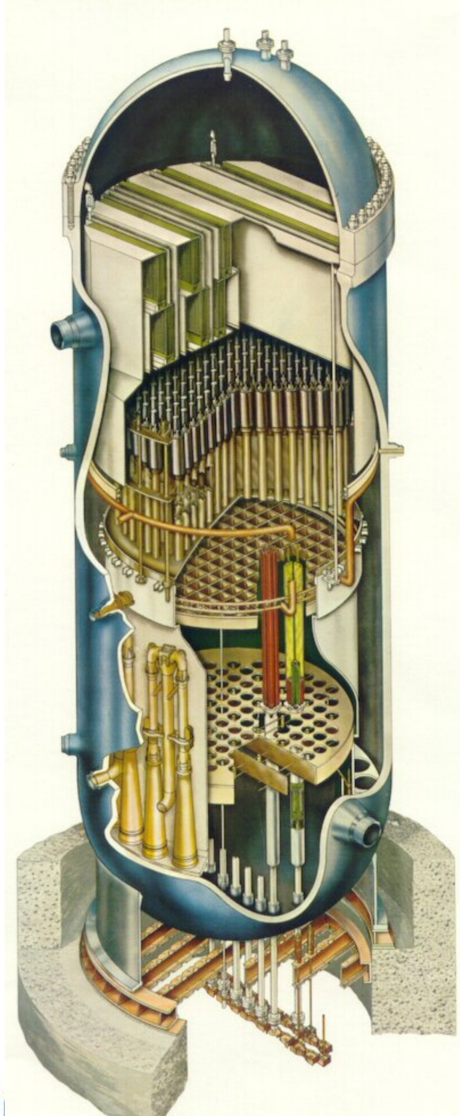
- Robotic inspection only, no personnel access
- Inspect the inlet and outlet nozzle-to-safe end welds at this time
  - Scanned on the inside surface
  - Special end-effectors mounted on the RPV inspection tool



BWR Pressure Vessel

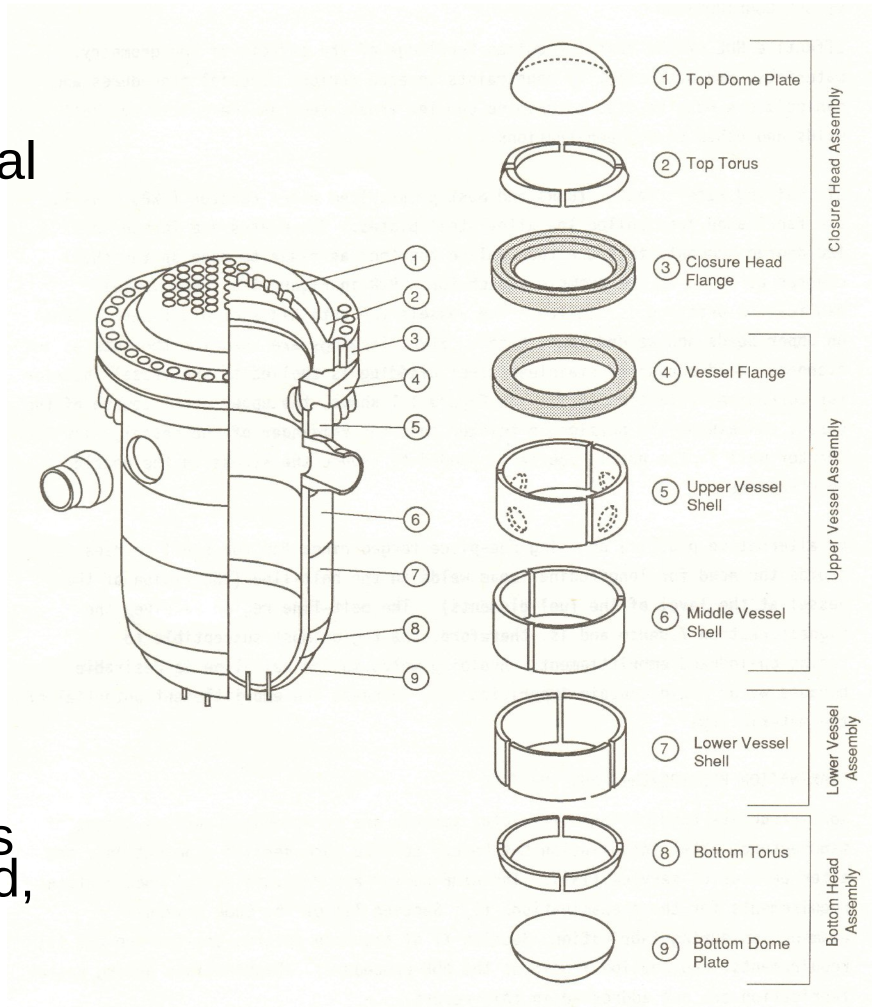
BWR vessels have complex internal structures, some of which cannot be removed

- Examination from the vessel outside surface is preferred (easier and cheaper)
  - Coverage limitations because of obstructions
- Examination from the inside surface usually is also necessary in order to comply with requirements for minimum coverage (90% of weld length)



Vessel Components

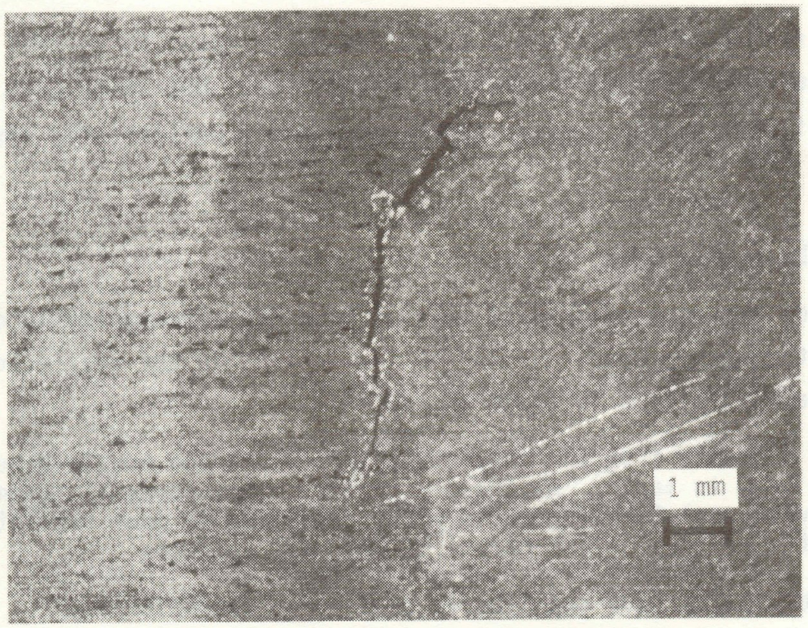
- Shell
  - Assembled from ring forgings or formed plates; vertical and horizontal welds
  - Nozzle-to-shell welds
  - Flange for bolting on the top head
- Top head
  - Assembly welds
  - Penetrations
  - Flange for bolting it onto the vessel
- Bottom head
  - Assembly welds
  - Penetrations
- Cladding
  - Inside surfaces of vessel and heads are covered with stainless steel clad, applied as weld metal



Inservice Inspection

- Base metal of the shell forgings or plates is not normally inspected
- Shell-to-shell welds are examined with ultrasonics
  - Critical area of concern is the inner part of the wall thickness, near the cladding
    - Higher stress and stress intensity
    - Higher embrittlement
    - Possibility of thermal shock

Crack in Backgouged Area of Vessel Shell Weld



Crack in root area of double-V weld in 10” thick vessel shell

Outline

- What's NDE?
- NDE for stainless steel and nickel-alloy components
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  - Dissimilar metal welds
  - Cast stainless steel
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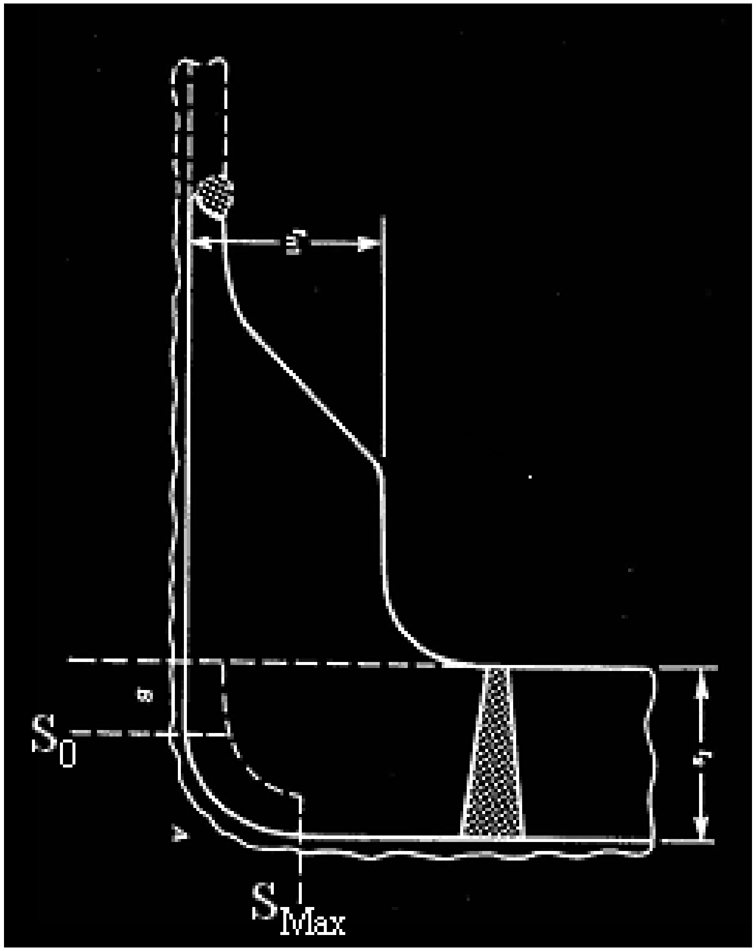
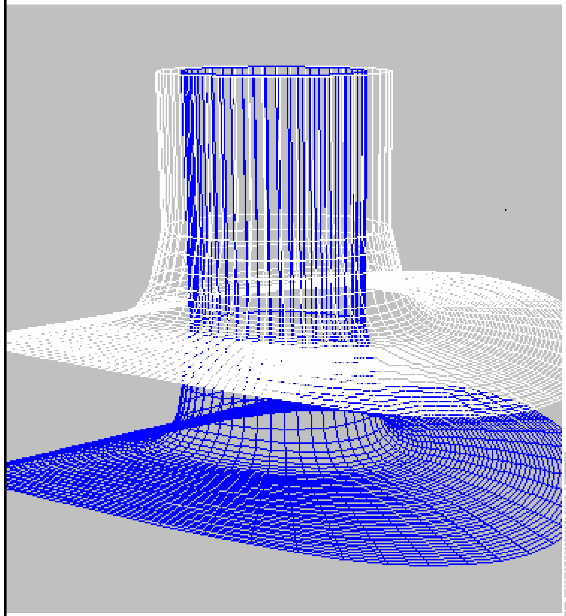
- NDE for reactor pressure vessels
  - Vessel overview
  - **Nozzles**
  - Underclad cracking
  - Qualification
  - Example of plant-specific vessel NDE issue
- Summary

Nozzle-to-Shell Welds and Nozzle Inner Radius



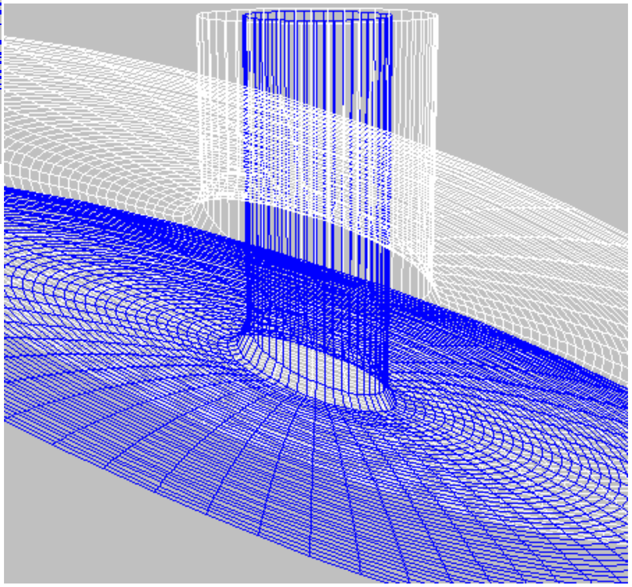
Examination of the nozzle is challenging due to the complex three-dimensional configuration

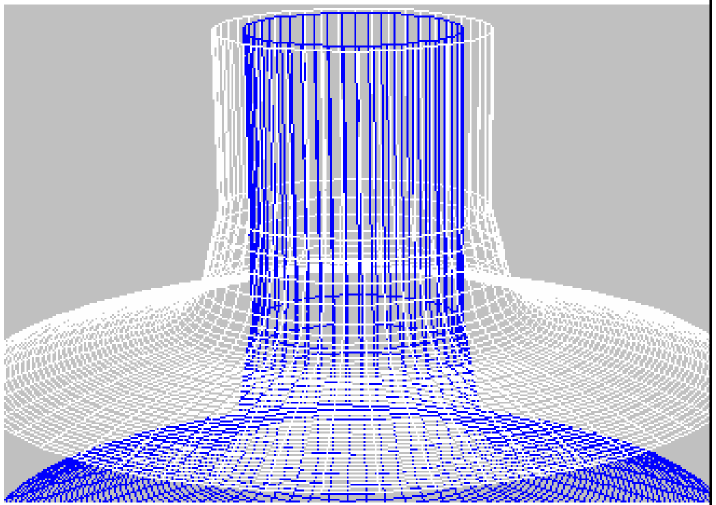
Vessel Nozzle Geometries



Cylinder-to-cylinder

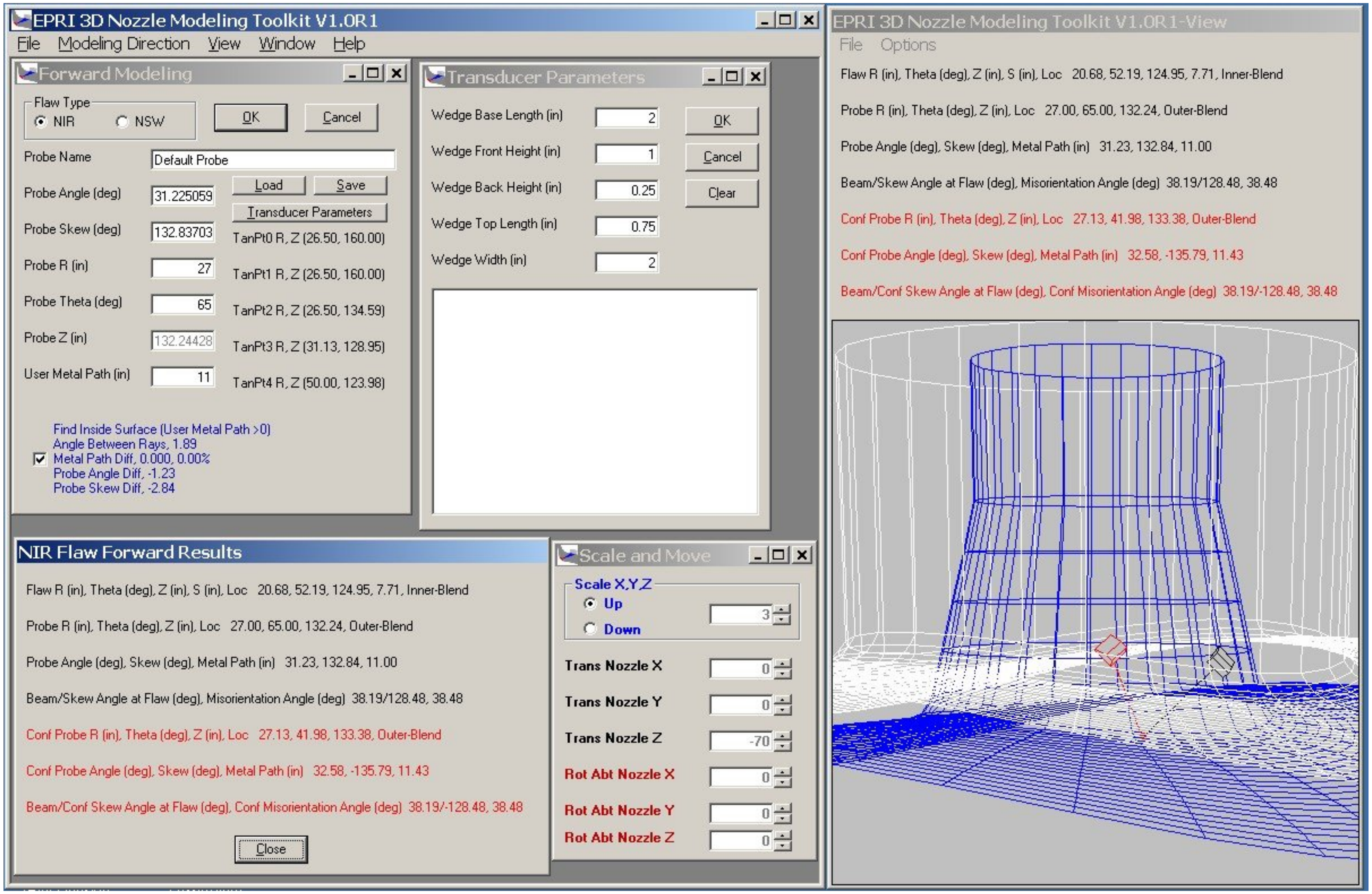
Off-axis



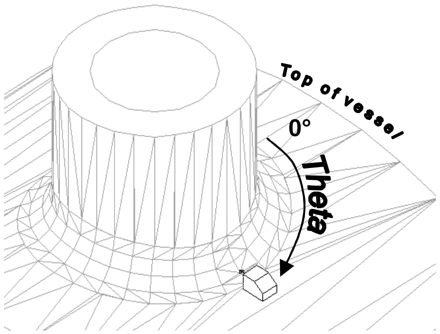


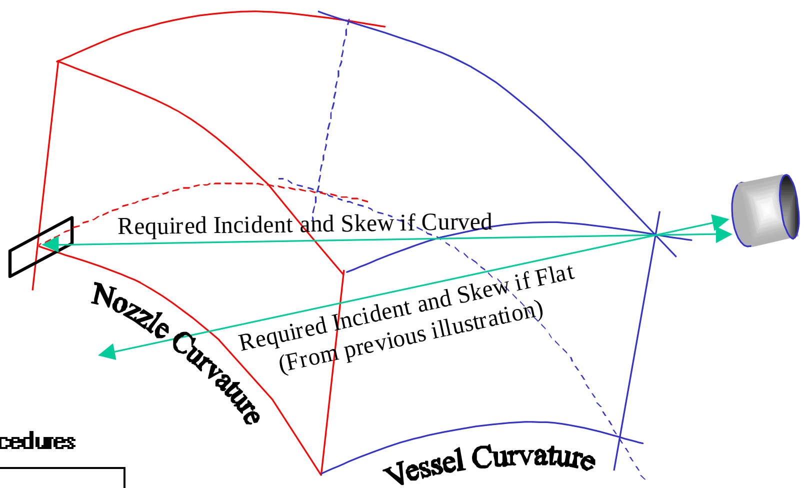
Cylinder-to-sphere

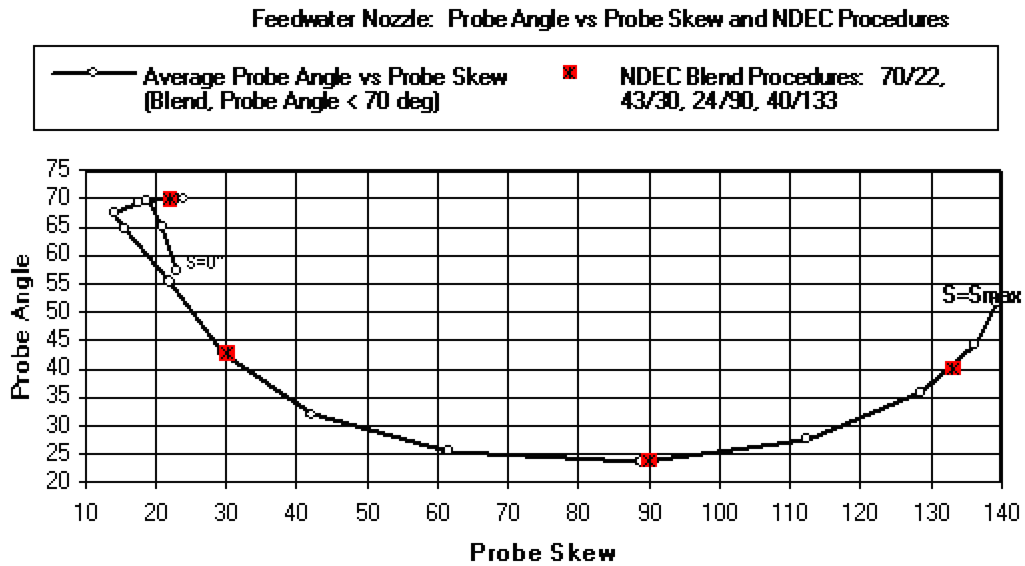
Determining Flaw Location in Nozzle Inner Radius by Geometric Modeling



Nozzle-to Shell Welds







Computer modeling is necessary to optimize the procedures, locate indications, and control the mis-orientation angles within qualified ranges

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  - **Underclad cracking**
  - Qualification
  - Example of plant-specific vessel NDE issue
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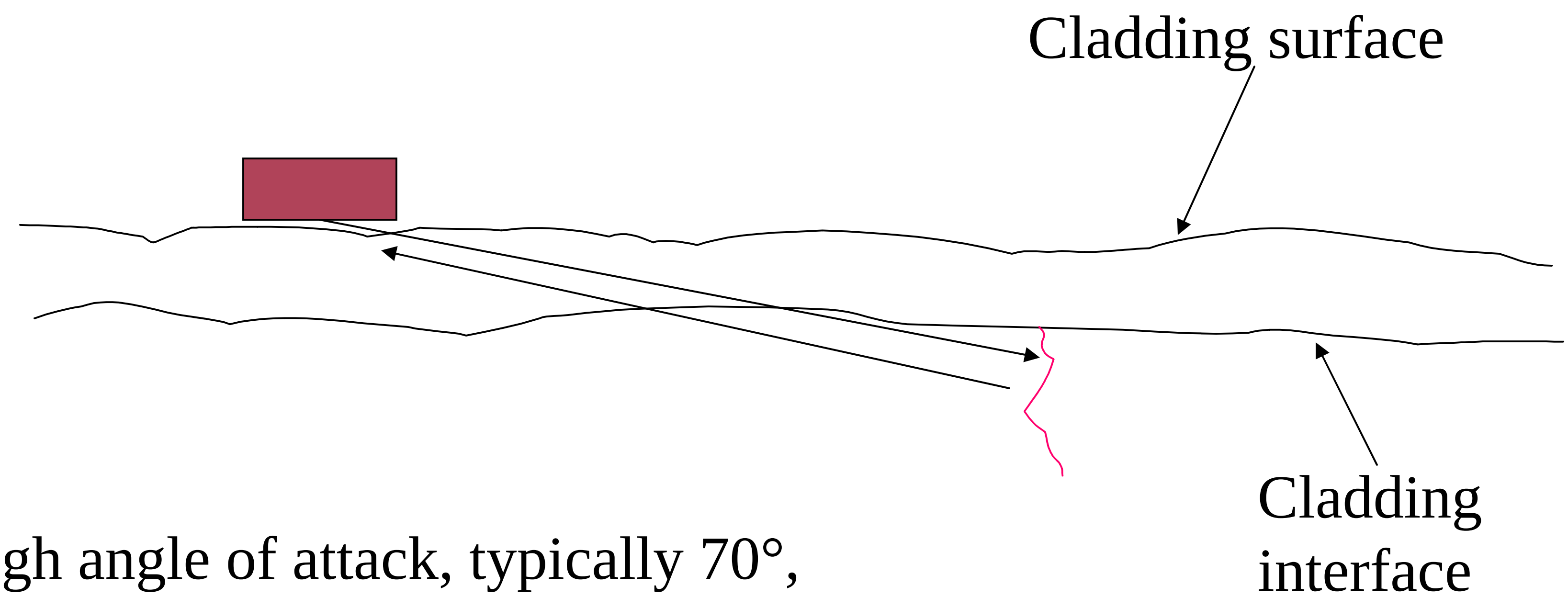
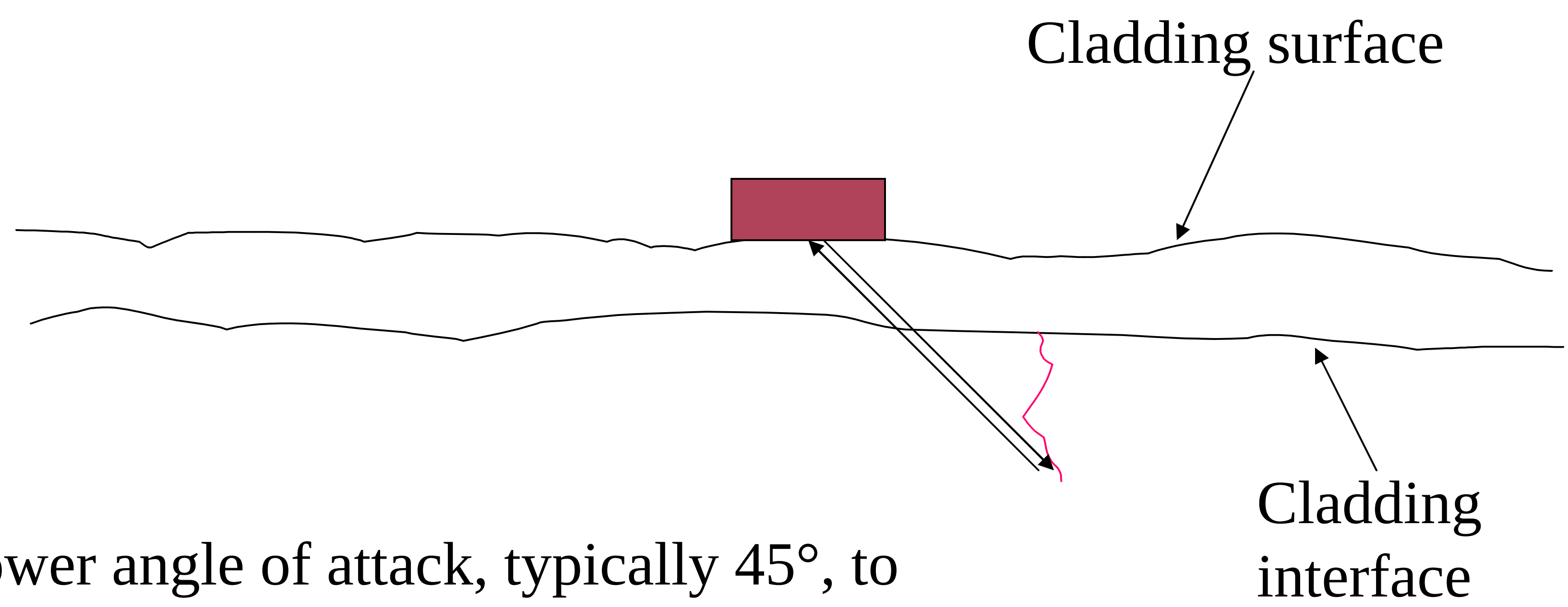
Examination Methods for Detection of Underclad Cracking



High angle of attack, typically 70°, to maximize reflectivity

Good for detection and length sizing, but depth sizing isn't accurate

Examination Methods for Depth Sizing of Underclad Cracking



Lower angle of attack, typically 45°, to maximize accuracy of locating tip

Good for depth sizing, but the response is low-amplitude and less reliable for initial detection

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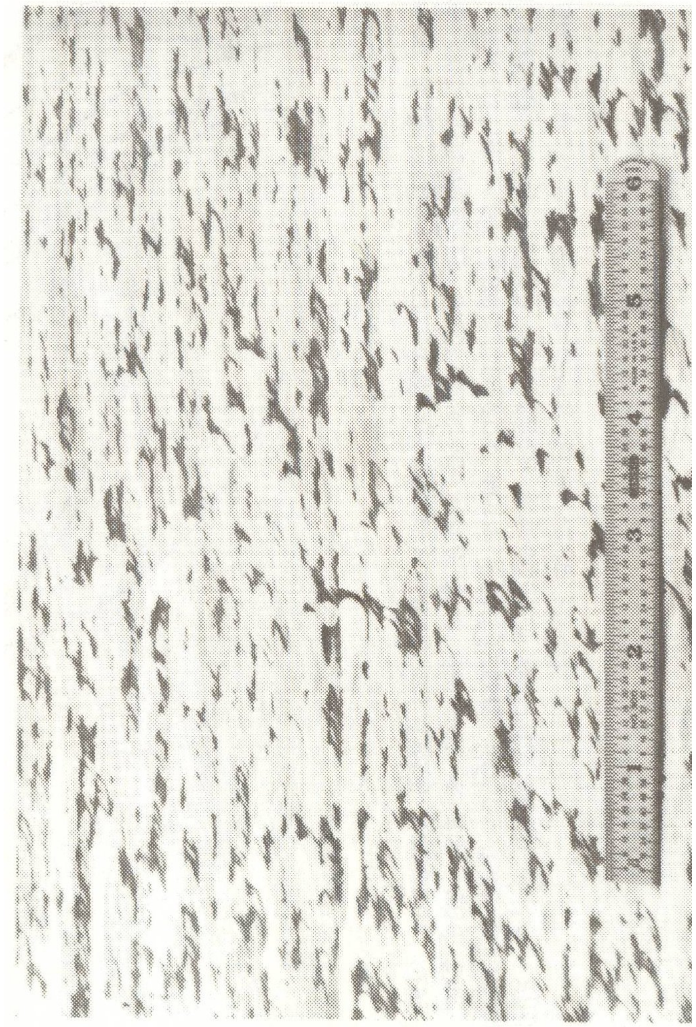
Cladding Effects

- Vessel cladding is weld deposited
  - It's stainless steel weld metal, so it's anisotropic
    - Highly attenuative
    - Noisy
    - Can change the direction of the sound beam in erratic ways
  - Surface condition also affects UT
- The good news – we don't have to detect flaws in the cladding itself, because no structural credit is taken for it

Vessel Cladding-Surfaces

Automated welding



Manual welding

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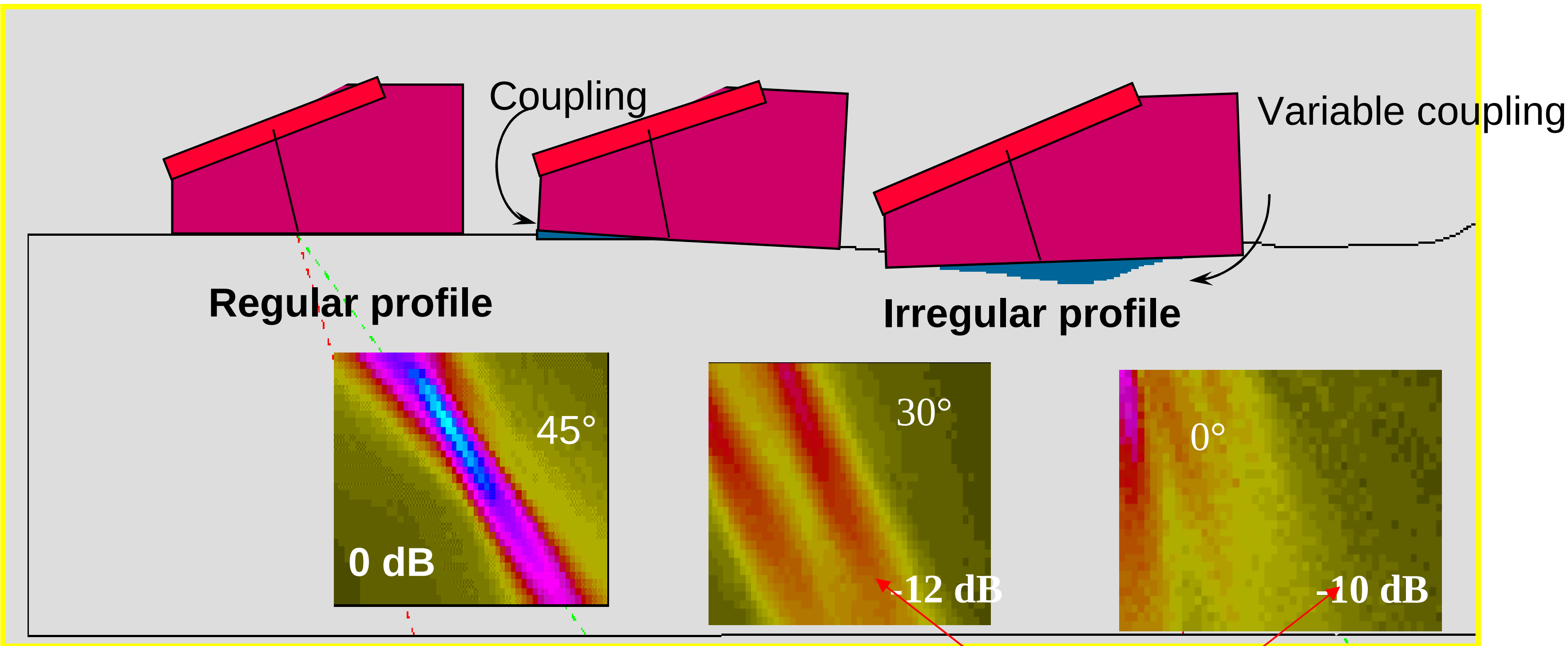
Cladding Roughness Lens Effect – Where's the Beam Going?



Nominal beam characteristics

Degraded and distorted beam

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Qualification

- Proof that NDE procedures, personnel, and equipment can detect and properly characterize flaws
    - Use of realistic flaws in realistic mockups
- Total cost of program to date is in tens of millions
    - – Mockup cost
    - – Administrative cost
- Qualification is impactful
    - – RPV procedure qualification may take months, and cost the vendor ~$0.5M

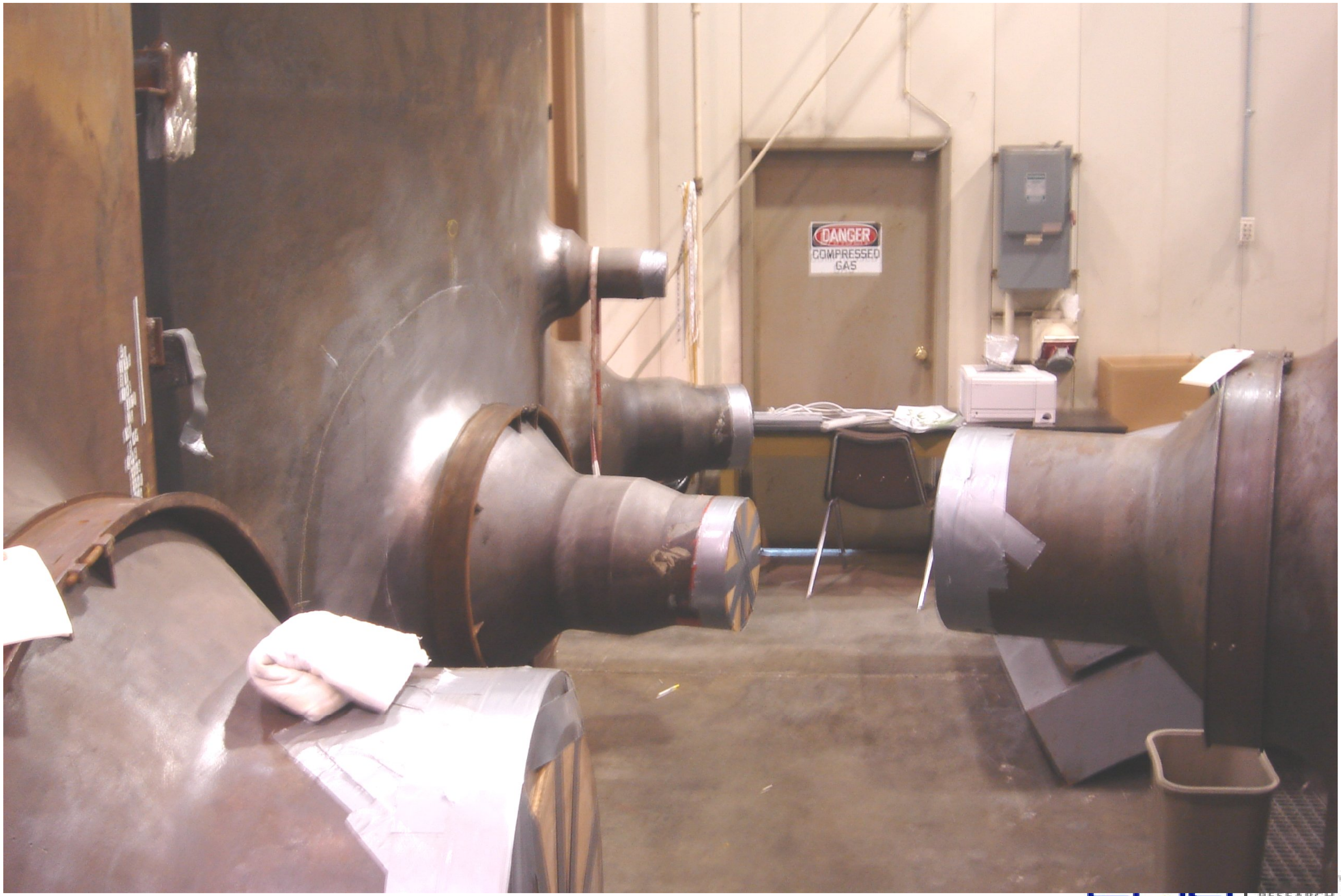
Qualification for RPV in the US

- Procedure qualification (NDE services vendor)
  - Several mockups must be examined
  - Total of 30-60 defects; all defects must be detected
  - Defect size measurement accuracy requirements
    - Length: RMS value of errors < 0.75 inch (19 mm)
    - Depth: RMS value of errors < 0.125 inch (3 mm)
- Personnel qualification (Vendor or utility personnel)
  - 10 – 20 defects
  - A small number of defects may be missed
  - A small number of false calls are allowed
  - Sizing accuracy criteria are the same as above

RPV Mockups

RPV Mockups

RPV Mockups



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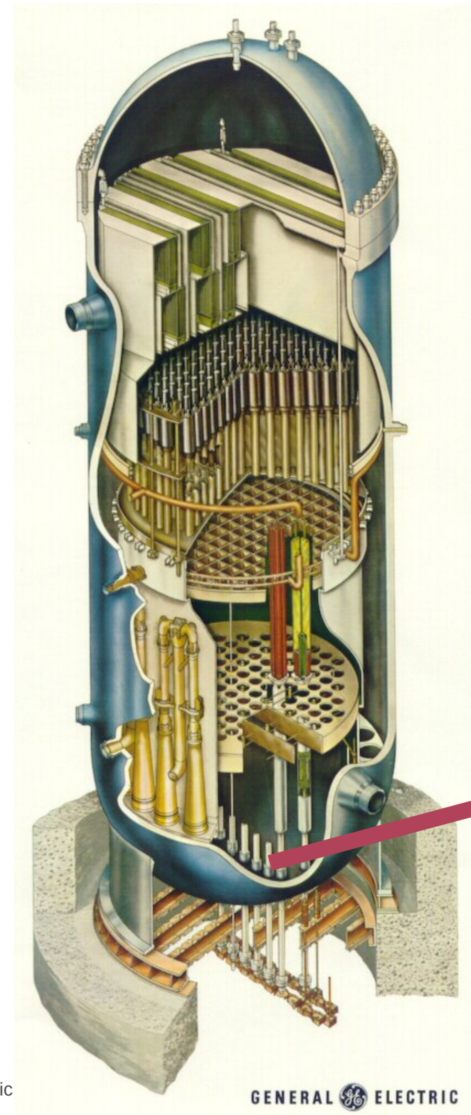
Practical Example of an RPV Issue: Leak from BWR RPV Bottom Head

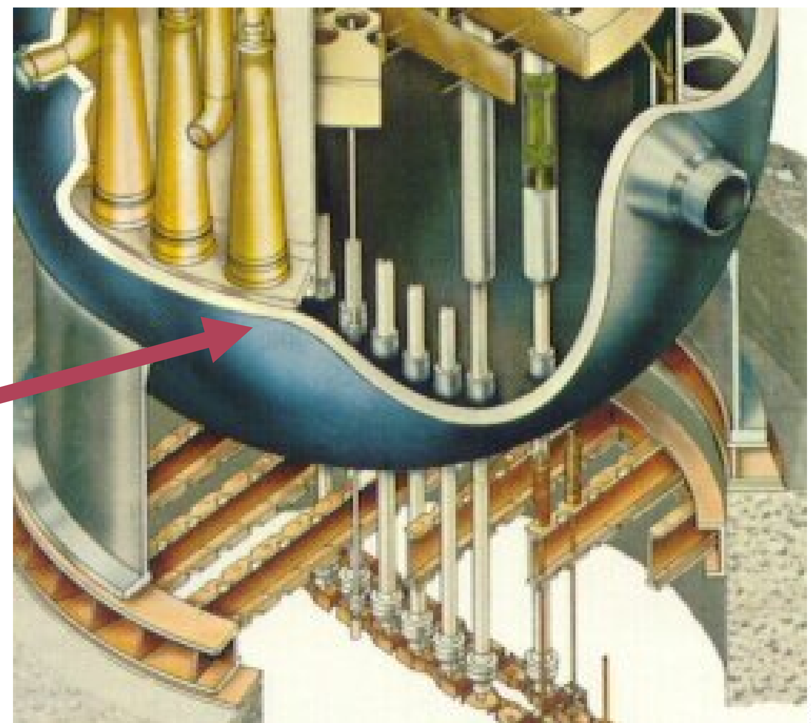
- Next several slides will illustrate an example of a vessel-related field inspection issue
  - Plant concern
  - EPRI response
  - Field application

Practical Example: Bottom Head Leak

Background

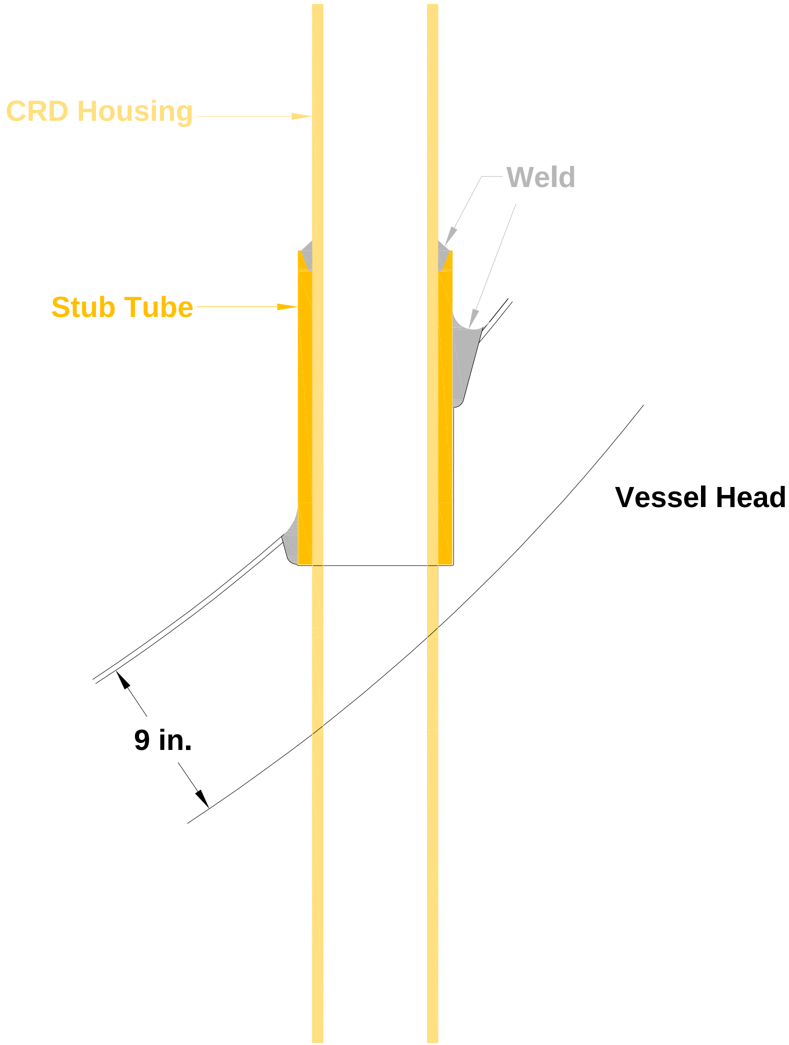


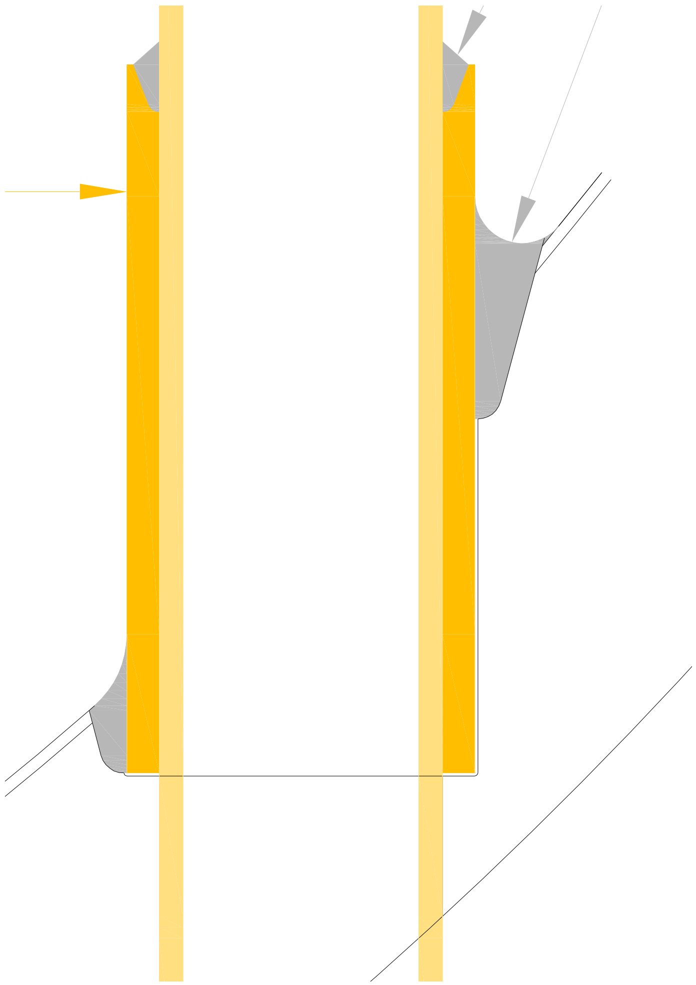
- **Bottom head of BWR RPV has many tubes coming through it (control rod drive mechanism housings, mostly)**
- **Nine Mile Point Unit 1 saw evidence of leakage under the head, at one of the CRDM penetrations**



Practical Example: Bottom Head Leak

Stub Tube Design





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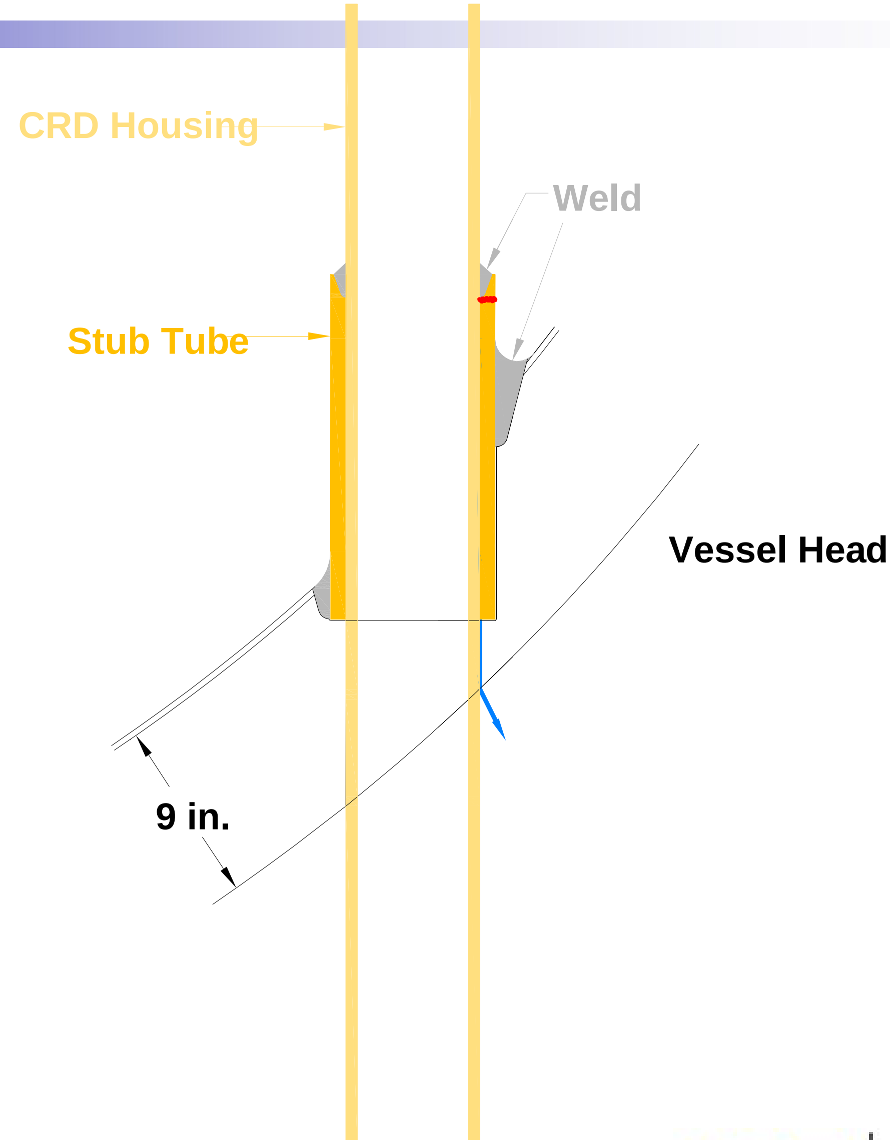
Practical Example: Bottom Head Leak

History of leakage through cracks in the tube

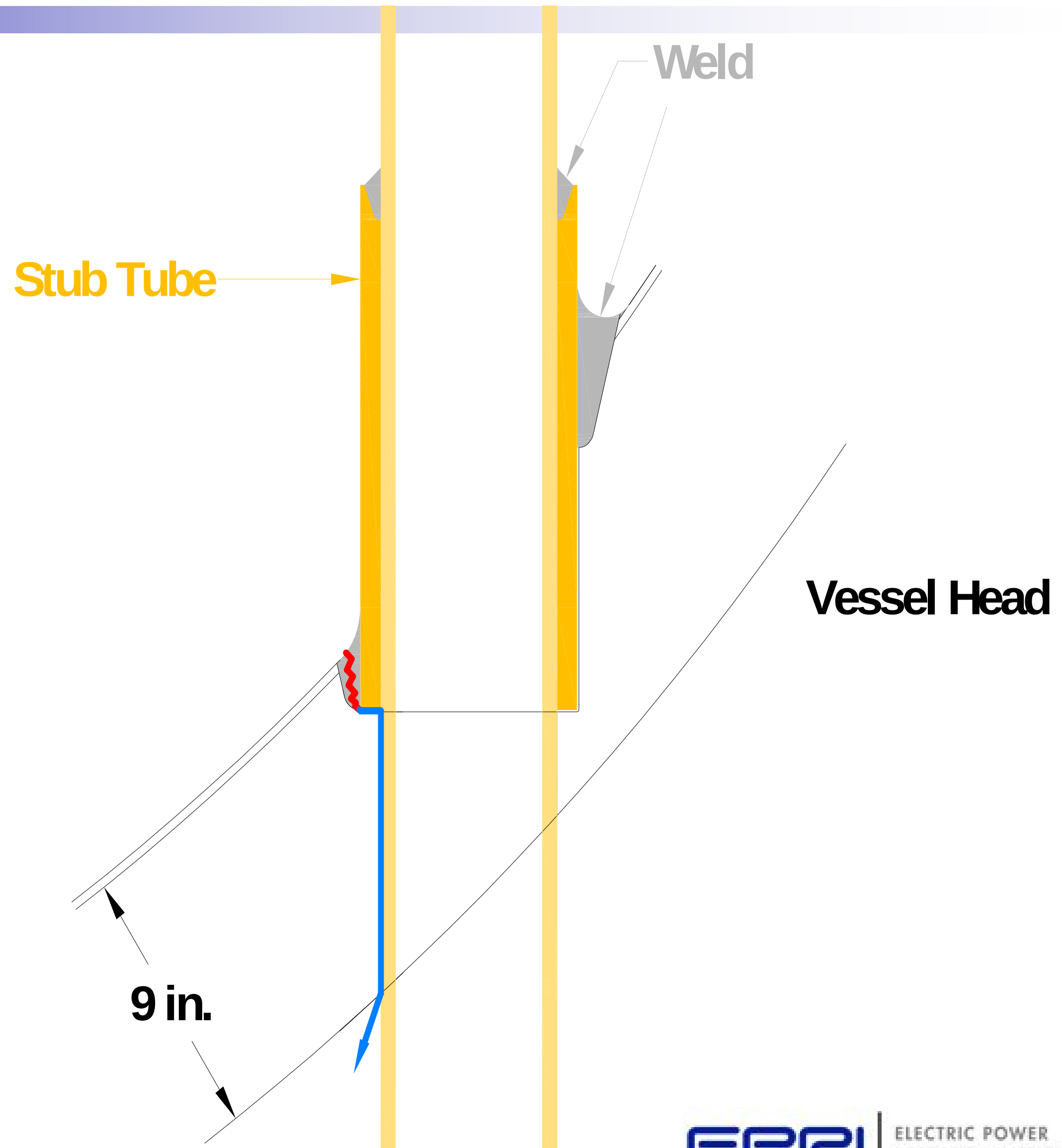
- This design has experienced several leaks due to cracking of the stub tube
  - Not a vessel integrity issue



Practical Example: Bottom Head Leak

Recent experience at a Japanese plant

- Recently a plant in Japan experienced a similar leak, but from a much more serious location: the stub tube-to-vessel weld
- If the weld crack grows into the vessel steel, the vessel faces a serious structural integrity issue

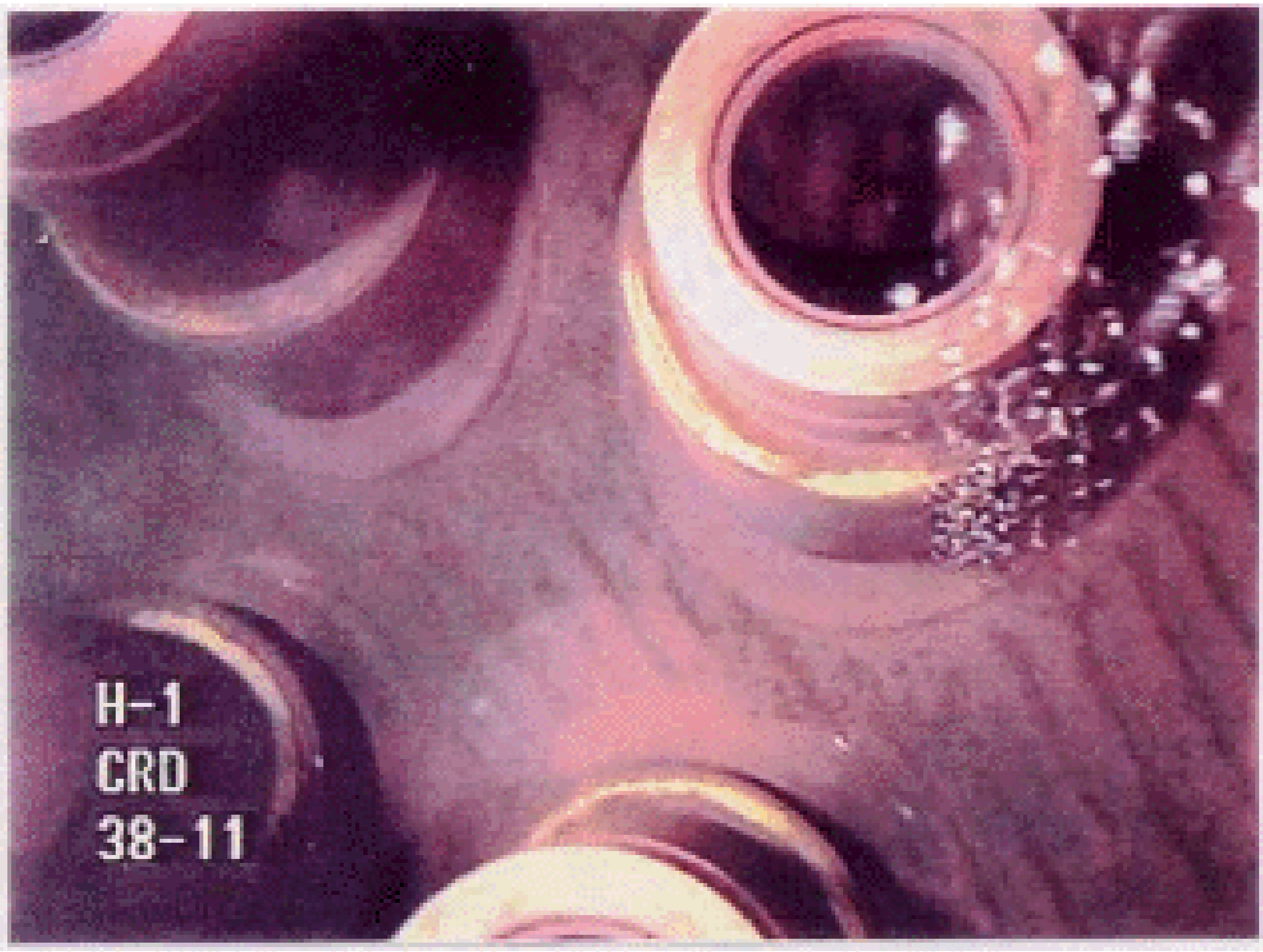


Practical Example: Bottom Head Leak

Recent Japanese leak from a weld crack

- Crack was repaired at a cost of $100M
- Crack did not grow into the vessel

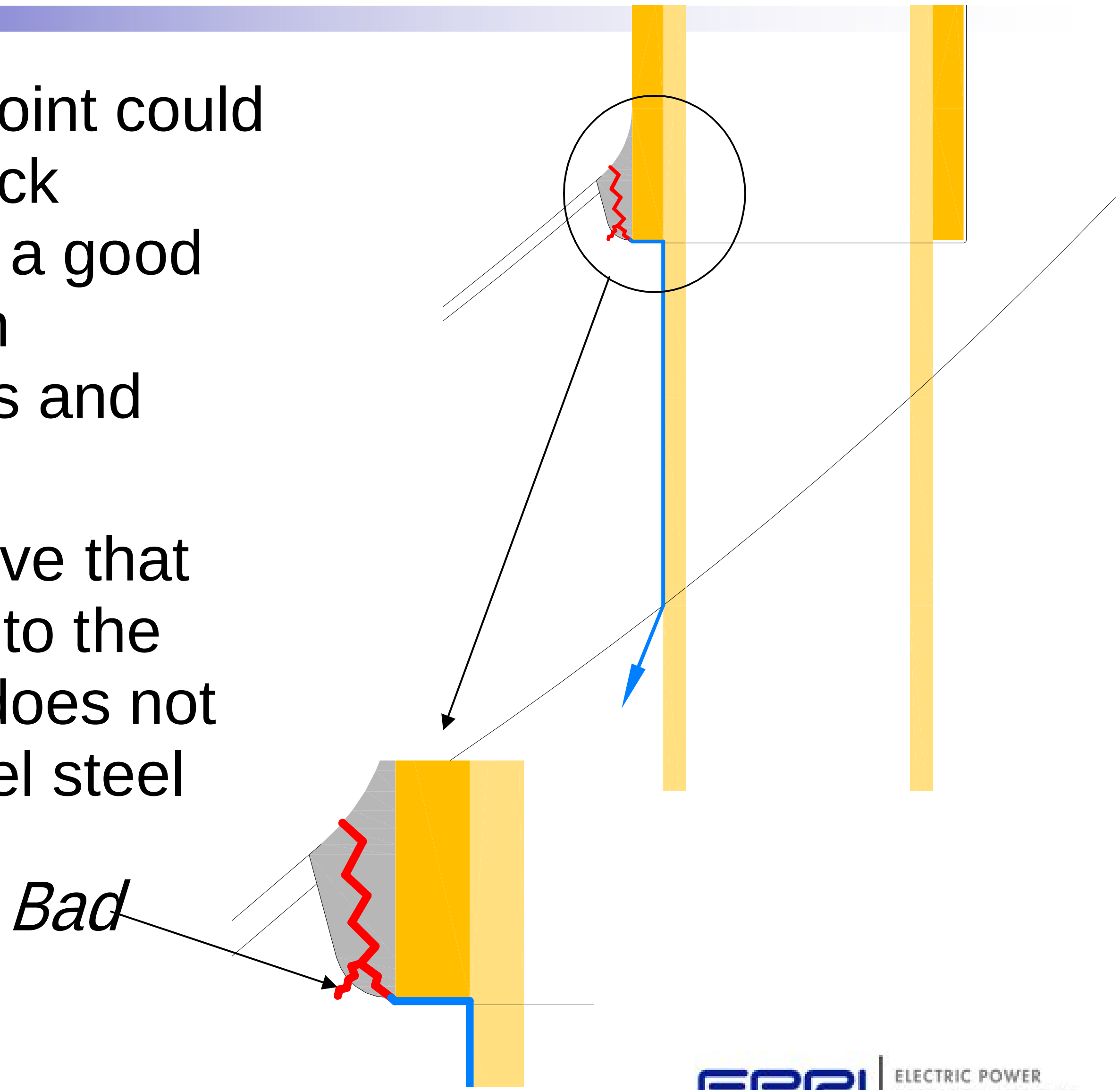
- Nine Mile Point planned a visual examination to see whether its leak was coming from a tube crack or a weld crack



Practical Example: Bottom Head Leak

Vessel integrity issue

- Maybe Nine Mile Point could live with a weld crack without repair, with a good argument based on materials properties and stress fields, but …
- The utility must prove that the crack is limited to the weld volume, and does not penetrate the vessel steel



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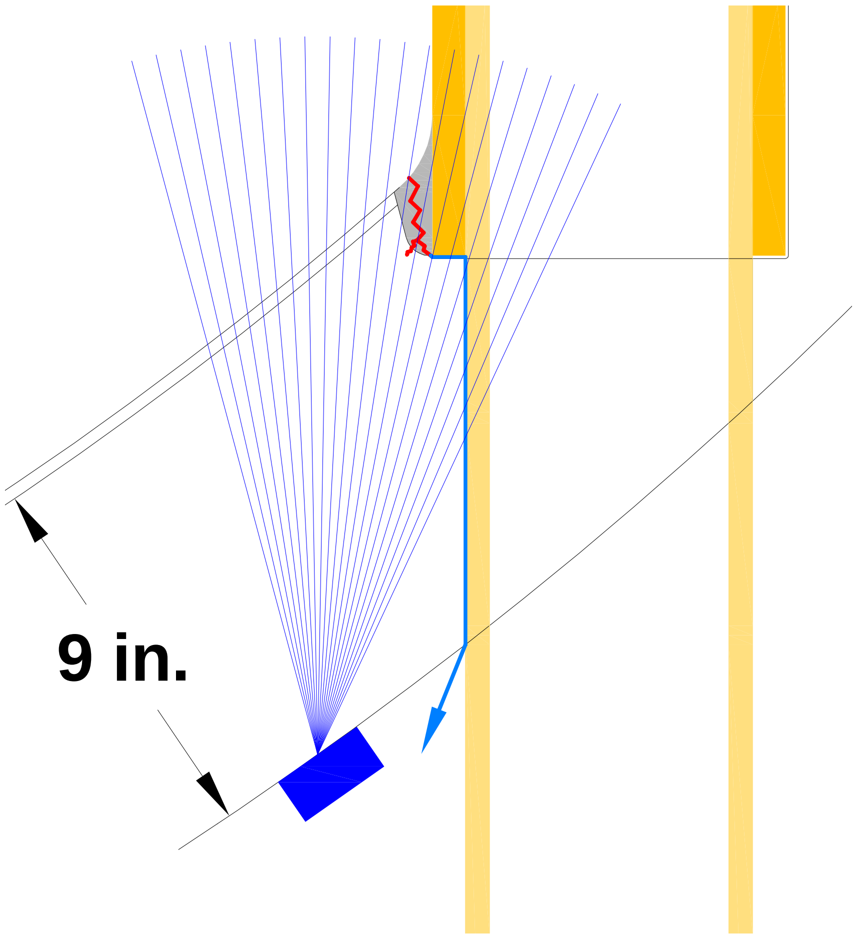
Practical Example: Bottom Head Leak

Phased Array UT Solution

- How to determine whether the crack is limited to the weld volume?
- Solution: use phased array ultrasound technology
  - Maximum coverage can be achieved from limited accessible scanning area



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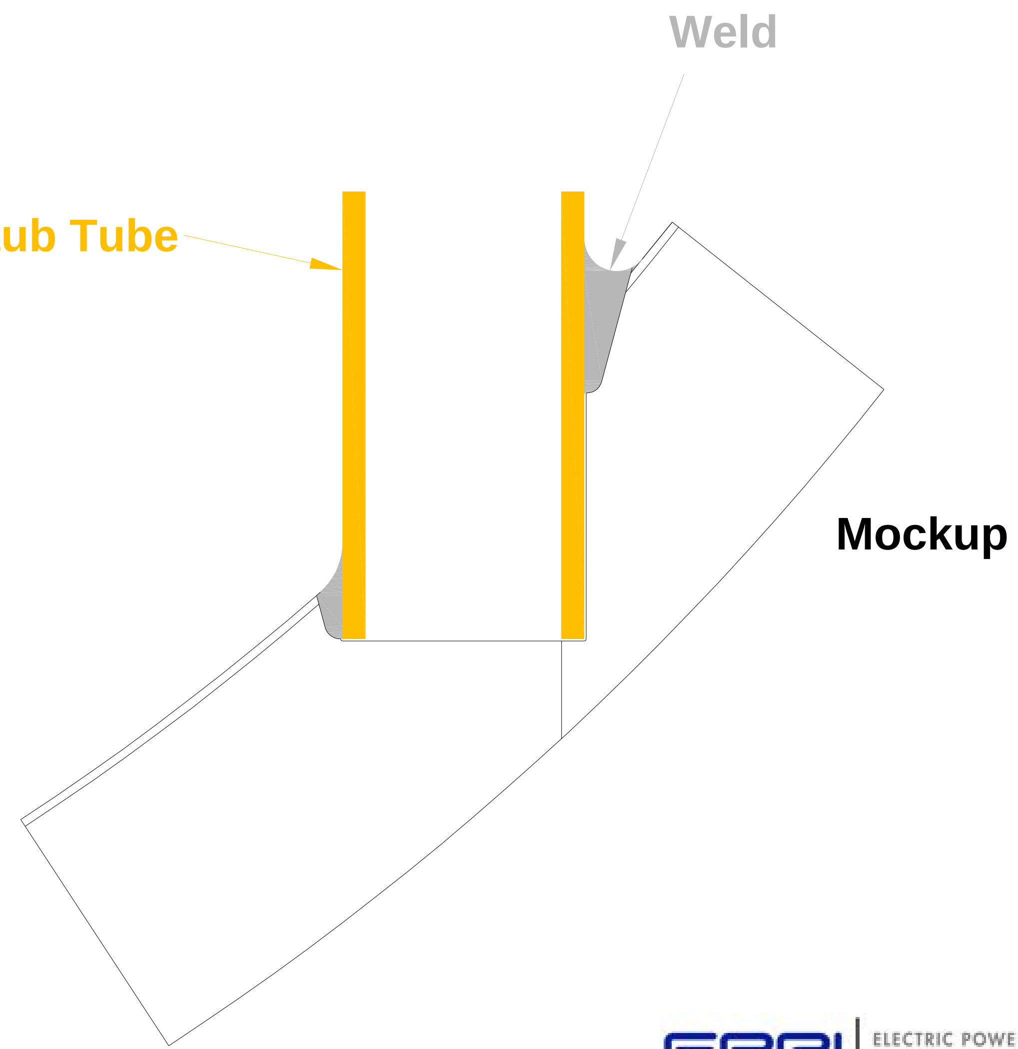
Practical Example: Bottom Head Leak

Mockup Development

Mockups

- Used existing material to build two realistic mockups

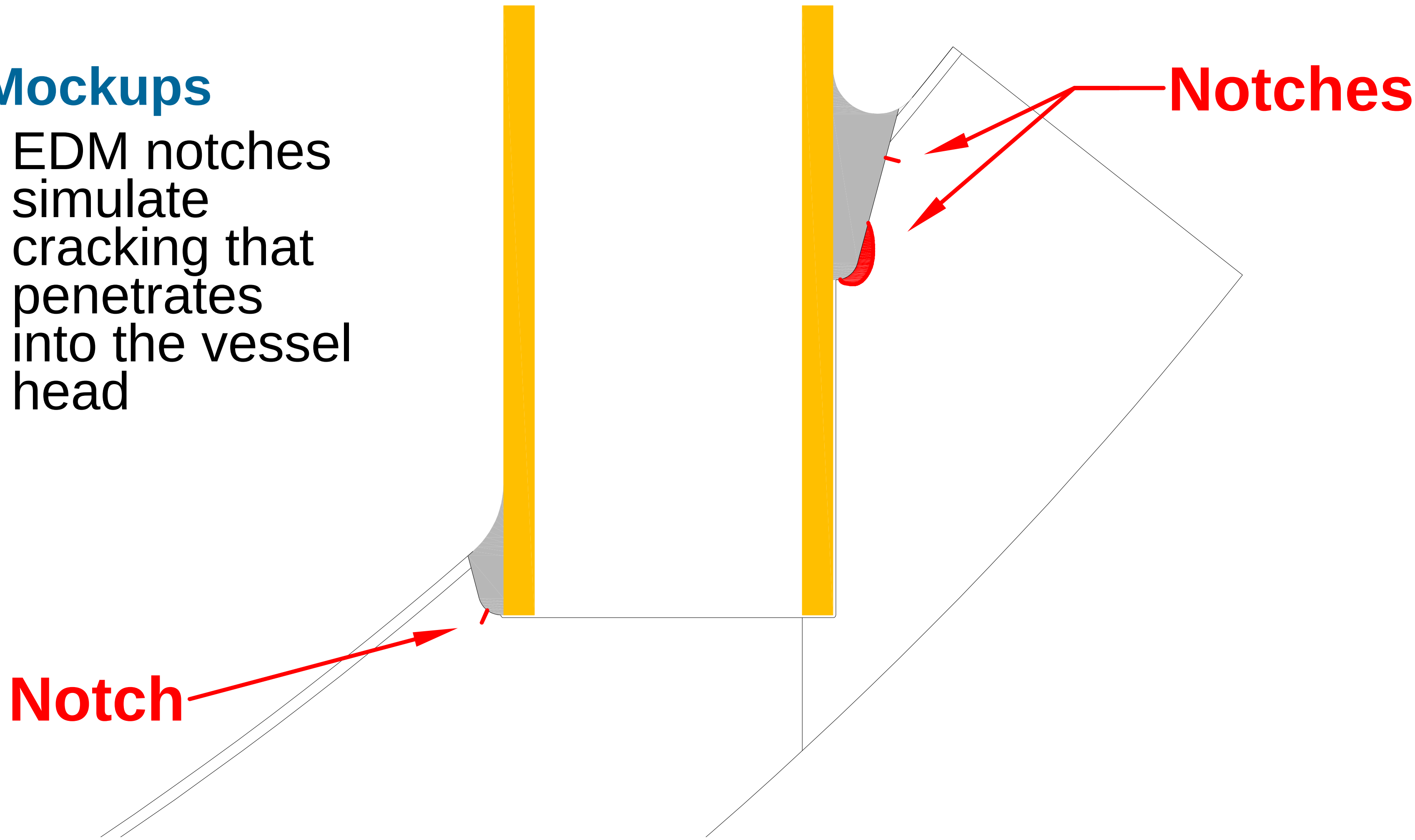


Practical Example: Bottom Head Leak

Mockup Development

Mockups

- EDM notches simulate cracking that penetrates into the vessel head



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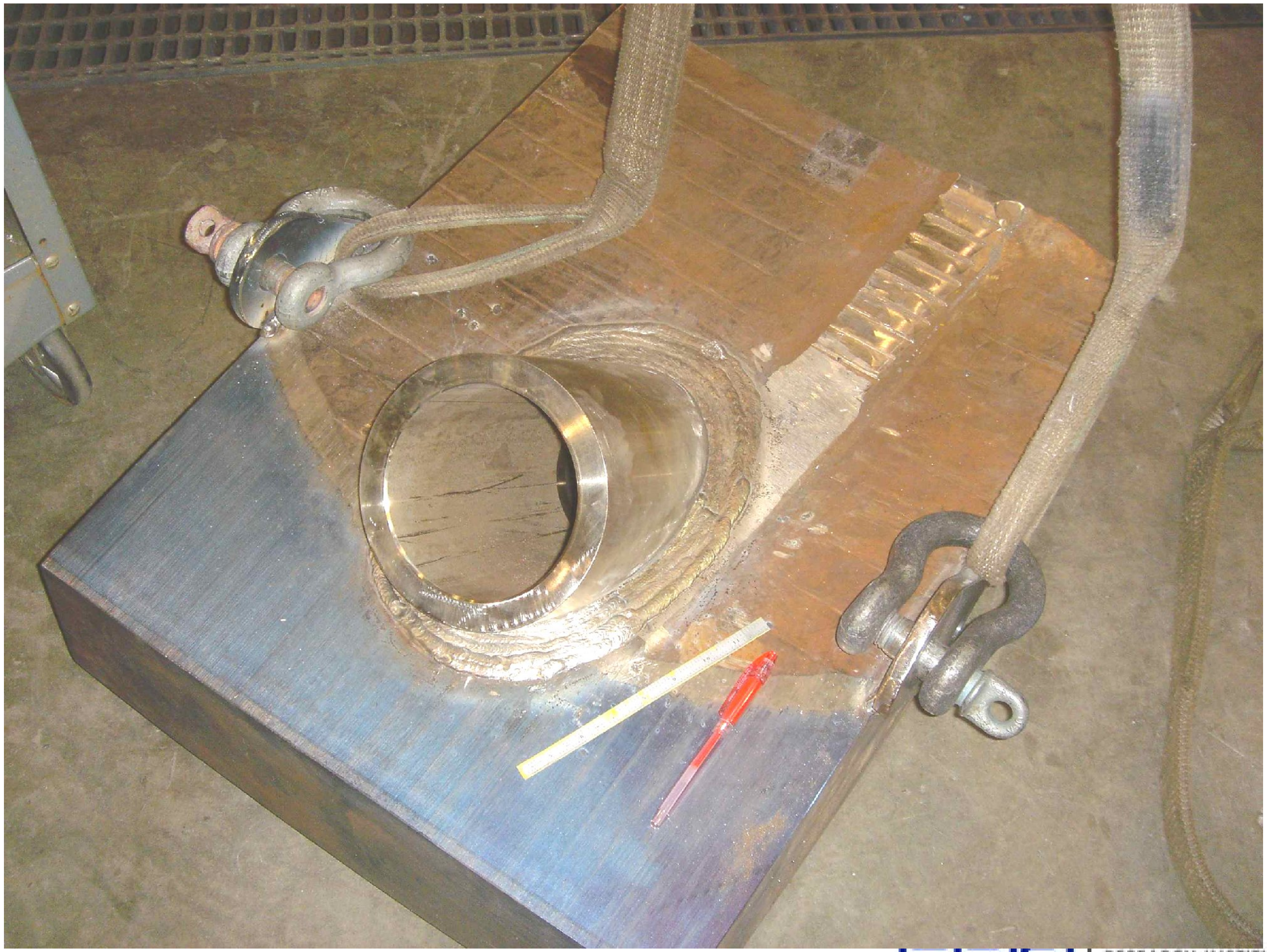
Practical Example: Bottom Head Leak

Mockup Development

Mockups



Practical Example: Bottom Head Leak

Mockup Development

Mockup notches

- Irregular tip shape

Practical Example: Bottom Head Leak

Ultrasonic Response from a Notch

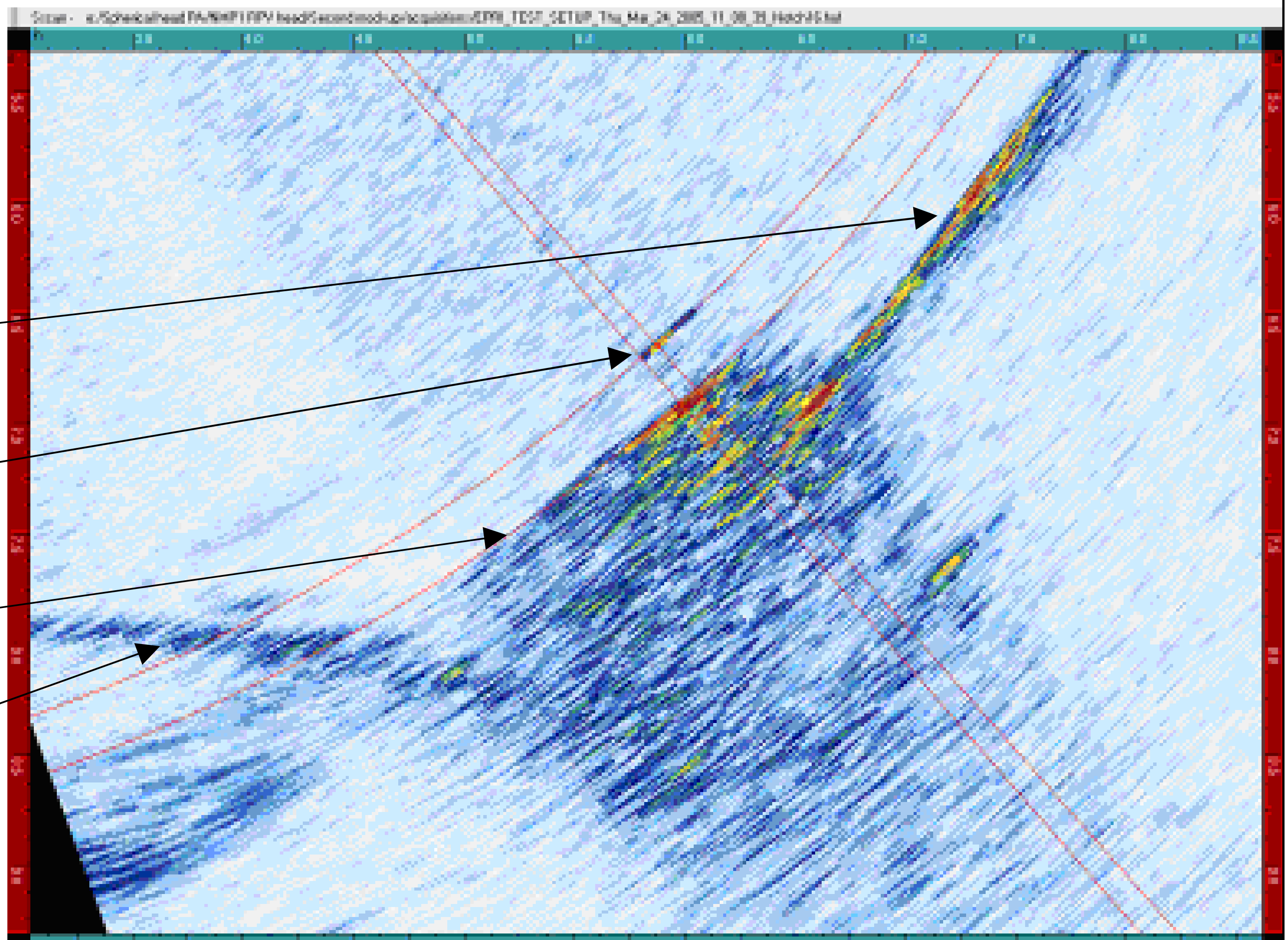
Sample image

Vessel penetration response

Notch tip response

Weld noise

Inside surface clad response



Practical Example: Bottom Head Leak

Inspection Capability

- All notches were detectable
- Sizing accuracy good

Notch	Location on weld prep	True penetration	Measured penetration	Error
11	Radius and top of taper	0.30	No measurement	
12	Radius and top of taper	0.30	0.32	+0.02
13	Radius	0.26	0.23	-0.03
14	Radius and top of taper	0.20	0.17	-0.03
15A (up)	Top of taper	0.25	0.24	-0.01
15B (up)	Bottom of taper	0.25	0.17	-0.08
15A (down)	Top of taper	0.25	0.20	-0.05
15B (down)	Bottom of taper	0.25	0.21	-0.04
16 (up)	Top of taper	0.30	0.29	-0.01
16 (down)	Top of taper	0.30	0.27	-0.03
17	Top of taper	0.26	0.22	-0.04
18	Top of taper	0.30	0.30	0.00
		Average error (inch)		**-0.03**

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Field Application

Inspection was not performed

- No visual evidence of further leakage
- No cracking was observed in stub tube-to-vessel weld
- Utility did not perform the UT examination
  - Radiation exposure
  - Logistical difficulty

Summary – Pressure Vessel

- Reactor pressure vessels are inspected with highest levels of quality
- Although ferritic materials are less challenging that austenitic materials to inspect, there are many geometric obstacles to overcome
- Qualification has improved the quality of inspections, but at a significant cost

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Summary - overall

- NDE is a key part of maintaining integrity of the pressure boundary
- Combinations of NDE methods are used to achieve full coverage of the areas of interest
- Qualification by practical test is required
- NDE can have a significant impact on outage scheduling
  – Planning is key